

# THERMOMETRY

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# OUTLINE

- What is thermometry?
- Contact thermometry
  - Thermistors
  - Thermocouples
  - Fiberoptic sensors
- Non-contact thermometry
  - Infrared thermometers
  - Magnetic Resonance Thermometry

# WHAT IS THERMOMETRY

- Thermometry is the process of measuring temperature.
- Temperature is basically a measure of the amount of kinetic energy, particles possess.
- A device which can measure the change of temperature is called thermometer.



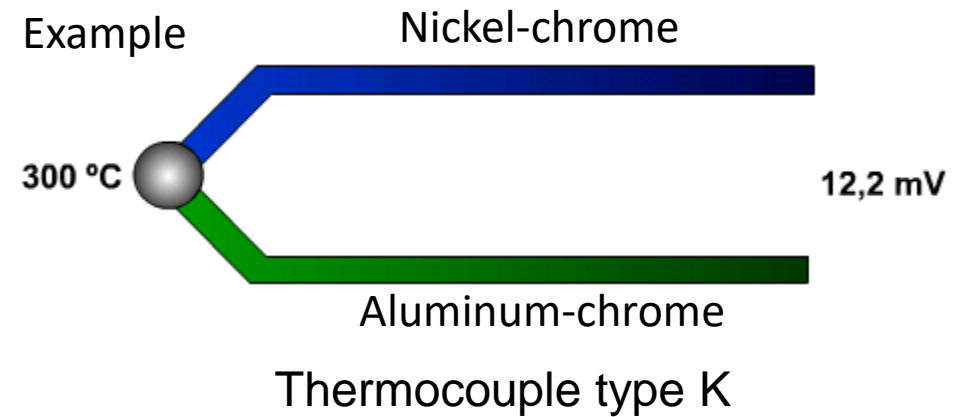
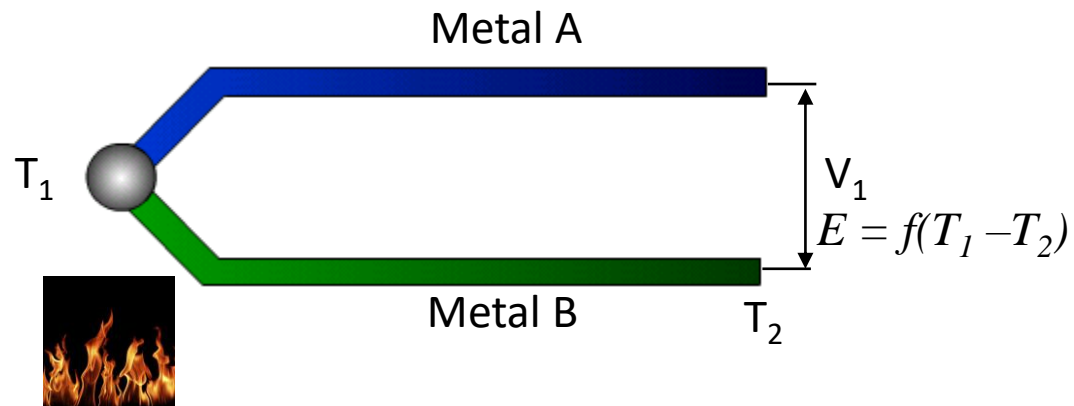
# TYPES OF THERMOMETERS

- During hyperthermia temperature is measured in 2 ways:
  - a) Contact
    - a) Thermistors
    - b) Thermocouples
    - c) Fiberoptic probes
  - b) Non-contact
    - a) Radiation thermometry
    - b) MRI

# CONTACT THERMOMETRY

## Thermocouple temperature probes

- Utilize the heat-induced potential difference from a junction of two different metals to measure temperature



- A circuit made by connecting two dissimilar metals produces a measurable voltage (emf-electromotive force) when a temperature gradient is imposed between one end and the other
- Thermocouple tables provide a voltage value with respect to a reference temperature. Usually the reference temperature is  $0\text{ }^\circ\text{C}$ . If your reference junction is not at  $0\text{ }^\circ\text{C}$ , a correction must be applied using the law of intermediate temperatures

# CONTACT THERMOMETRY

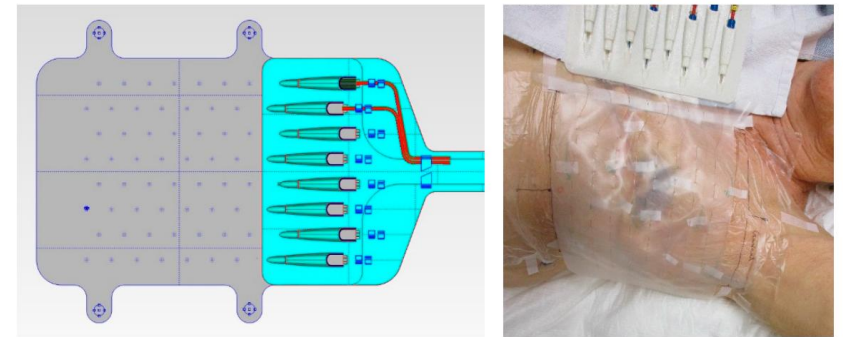
## Thermocouple temperature probes

### Advantages

- Fast response
- Small size (12  $\mu\text{m}$  diameter)
- Accurate
- Long term stability
- Cheap
- Ease of fabrication

### Disadvantages

- Need for reference temperature
- Small output voltage  $\rightarrow$  Low sensitivity
- Potential interactions between device and heating source



Thermal Monitoring Sheet, Medlogix (Rome, Italy);  
From Akke Bakker et al., 2020



48-channel thermocouple thermometry system for invasive prostate monitoring during Interstitial hyperthermia;  
From Titania Juang et al., 2009

# CONTACT THERMOMETRY

## Thermistor temperature probes

### What is a thermistor?

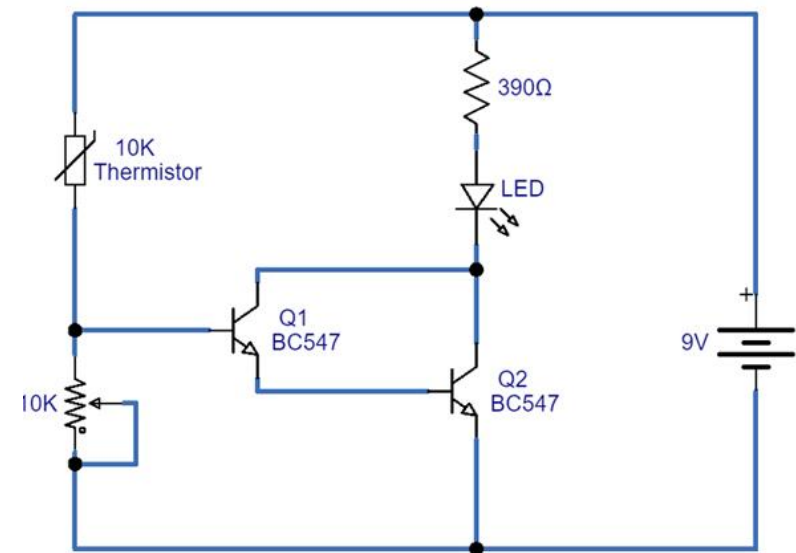
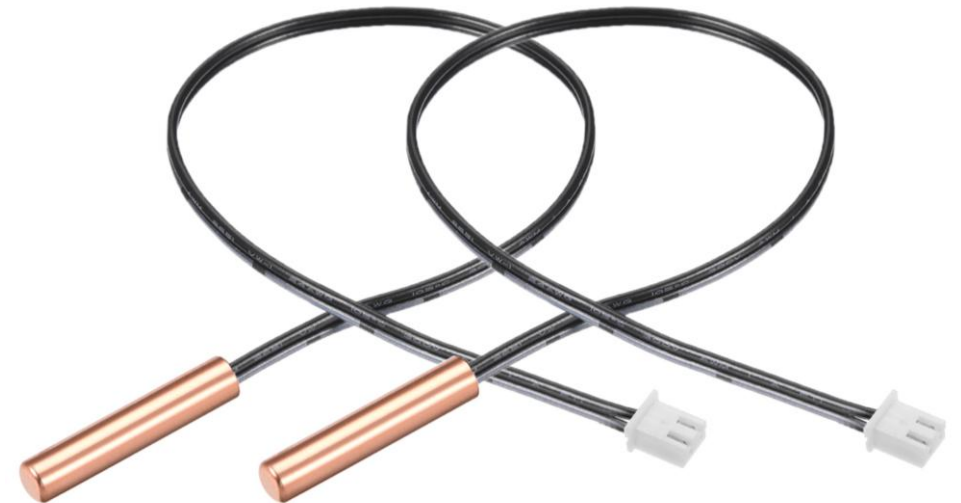
- a semiconductors made of ceramic materials of which resistance varies with temperature

### Types of thermistors

-Negative temperature coefficient (NTC) → The resistance decreases as temperature increases (opposite to the way metals react).

-Positive temperature coefficient (PTC)

The resistivity of thermistors for biomedical applications is between  $0.1$  and  $100 \Omega \cdot m$



# CONTACT THERMOMETRY

## Thermistor temperature probes

### Advantages

- Small in size (0.5 mm in diameter)
- High sensitivity to temperature changes
- Excellent long-term stability characteristics

### Disadvantages

- Nonlinear
- Self heating
- Limited range

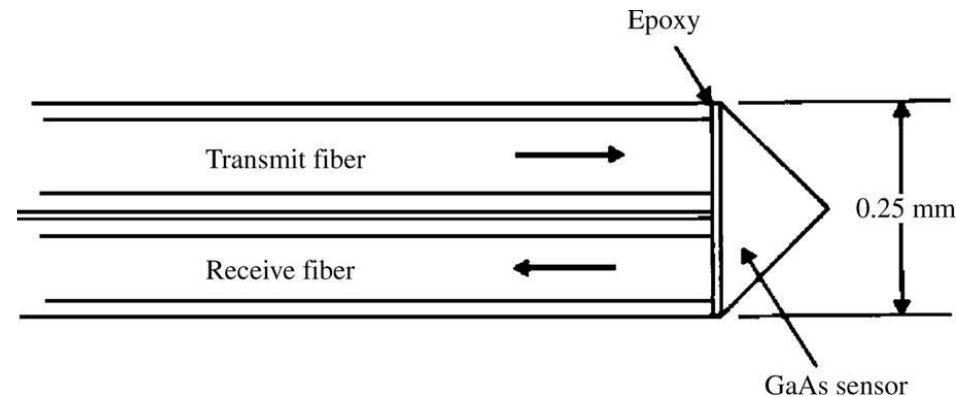




# CONTACT THERMOMETRY

## Fiberoptic temperature probes

- A fiber-optic temperature sensor exploits **temperature dependencies in optoelectronic materials**



- A **prism-shaped single crystal** undoped GaAs is **epoxied** at the ends of two side-by-side optical fibers
- One **fiber tx** light passes through the **GaAs** and is collected by the other fiber for detection on the readout instrument
- Some of the optical power is absorbed, by the process of raising valence-bands electrons, cross the forbidden energy gap into the conduction band
- Because the forbidden energy gap is a sensitive function of the material's temperature, **the amount of power absorbed increases with temperature**

# CONTACT THERMOMETRY

## Fiberoptic temperature probes

- The fiber optic probes are **immune to ambient EM radiation** which makes them the most attractive temperature system when used in combination of some form of EM energy, e.g. MW hyperthermia and ablation for cancer therapy or RF for cardiac ablation

### Advantages

- Small
- Accurate
- Does not interfere with RF

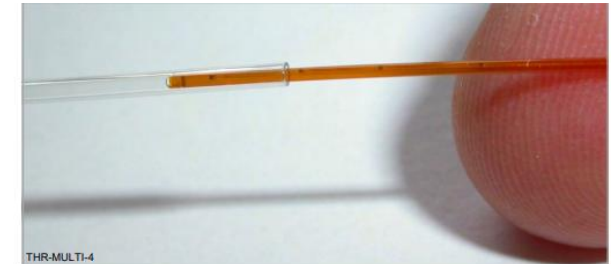
### Disadvantages

- Fragile
- Expensive

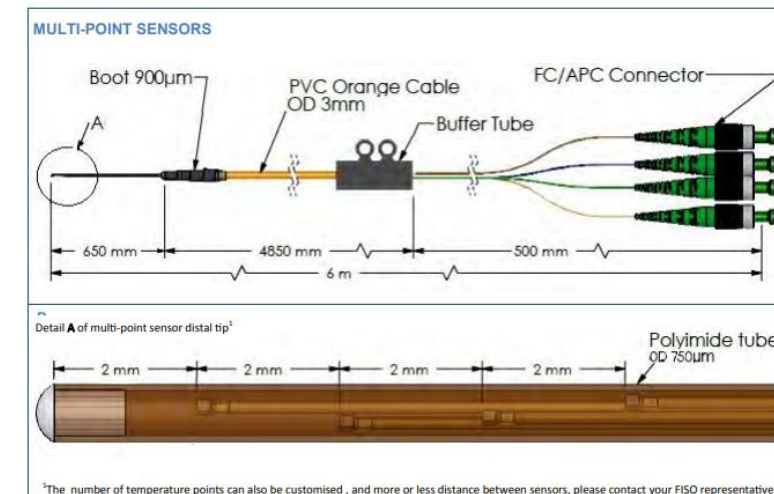


BSD-2000 8-port Temperature Monitoring

Multipoint Fiberoptic temperature sensor developed by FISO



THR-MULTI-4



# NON-CONTACT THERMOMETRY

## Radiation thermometry

- Bodies above 0 K (absolute zero) → radiates electromagnetic (EM) power
- **No-contact required** to measure temperature
  - Previous temperature-measuring techniques measure the temperature of the sensor. Sensor in contact with the subject long enough for its temperature to become the same as the subject
  - IR thermometry devices receive radiation proportional to the temperature of the subject
- At room temperature, the spectrum is predominantly in the far- and extreme-far **infrared** regions



# NON-CONTACT THERMOMETRY

## Radiation thermometry

- **Black body**, ideal thermal radiator: it absorbs all incident radiation and emits the maximum possible thermal radiation
- The radiation emitted from a body is given by **Planck's law multiplied by emissivity  $\varepsilon$** , spectral radiant emissivity
- Emissivity is the extent by which a surface deviates from a blackbody

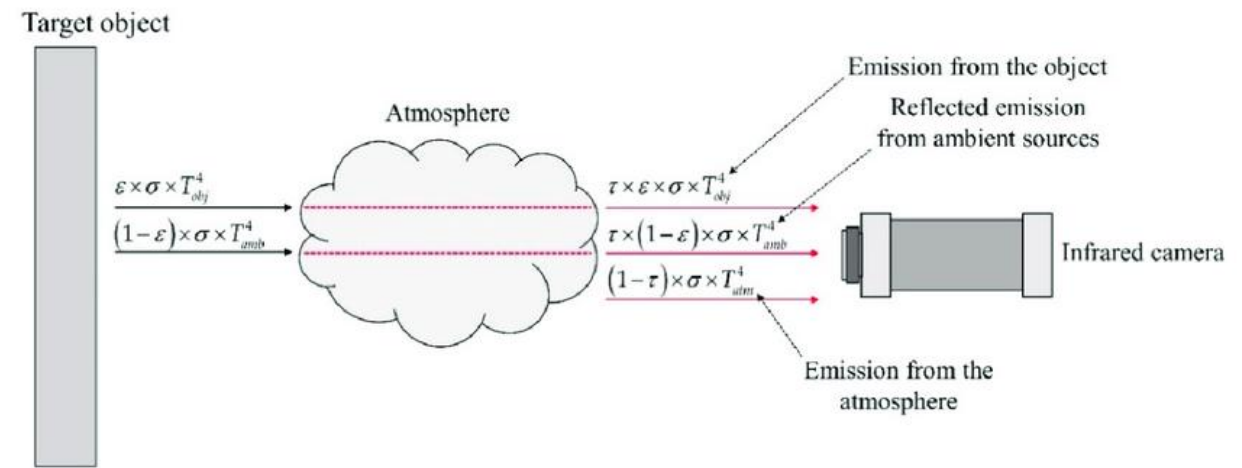
( $\varepsilon = 1$  for blackbody)

$$W_{\lambda} = \frac{\varepsilon C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} \quad (\text{W/cm}^2 \cdot \mu\text{m})$$

$$C_1 = 3.74 \times 10^8 \text{ W} \cdot \mu\text{m}^4 / \text{cm}^2$$

$$C_2 = 1.44 \times 10^4 \mu\text{m} \cdot \text{K}$$

T is the black body temperature in K



# NON-CONTACT THERMOMETRY

## Infrared 2D Thermometry

- With infrared cameras the surface temperature of the body can be measured

### Advantages

- Real time 2D temperature distribution

### Disadvantages

- Not very accurate absolute values
- Calibration is sensitive to motion and surface material changes



FLIR thermal camera



Superficial IR temperature monitoring during hyperthermia with wIRA Heckel system.

# NON-CONTACT THERMOMETRY

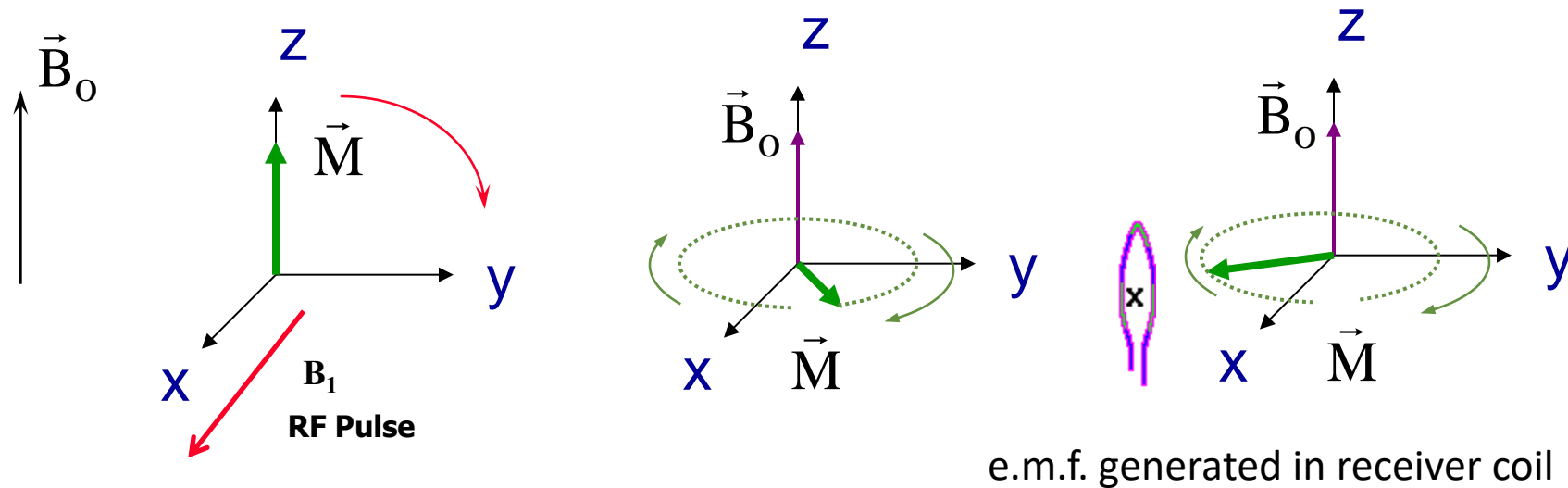
## Magnetic Resonance Thermometry

Magnetic Resonance (MR) signals contains information about temperature variations

Temperature mapping can be obtained from parameters that are temperature-sensitive:

- Proton density
- $T_1$  Longitudinal relaxation time
- Diffusion coefficient
- Proton resonance frequency

# NUCLEAR MAGNETIC RESONANCE



e.m.f. generated in receiver coil

$$\frac{d}{dt} \vec{M} = \vec{M} \times \gamma \vec{B}$$

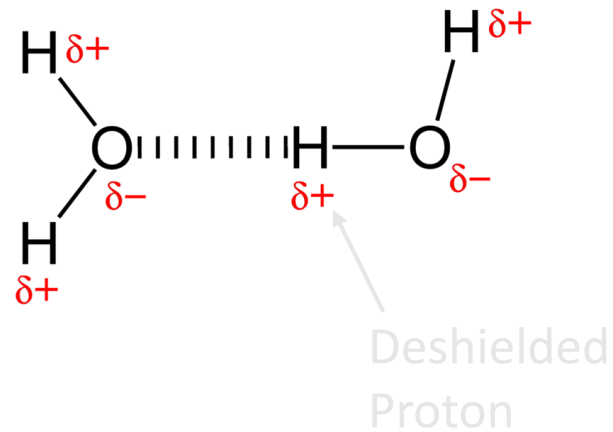
$$\omega = \gamma |\vec{B}_0| \quad \text{Larmor Frequency}$$

## Thermometry Measurement:

Temperature Change causes change in Larmor Frequency

# H<sub>2</sub>O CHEMICAL SHIFT

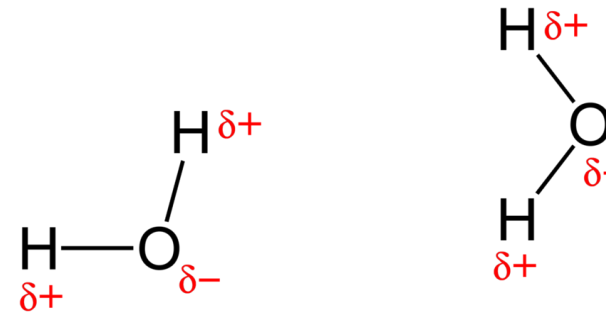
## Lower Temperature



**Higher** Proton Resonant Frequency

On average molecules are in “ice-like” H-bonded state.

## Higher Temperature



**Lower** Proton Resonant Frequency

On average molecules are “free” H<sub>2</sub>O molecules. The H-bonded state is less prevalent.



# PRFS: LINEARITY & TISSUE INDEPENDENCE\*

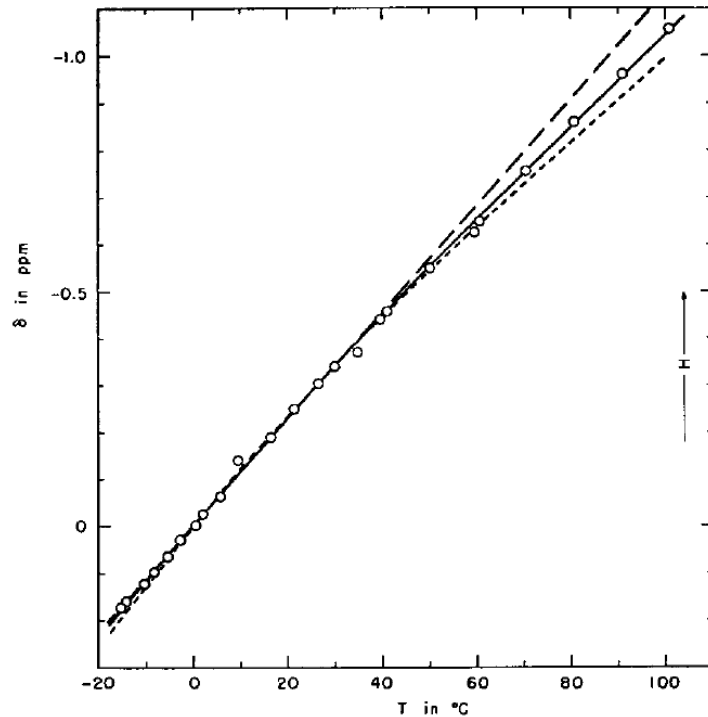


FIG. 1. Chemical shift of water as a function of temperature,  $\delta_{\text{H}_2\text{O}}$  at  $0^\circ\text{C}=0$ .  $\circ$ , Experimental data; —, straight line; - - - -, susceptibility corrected shift line.

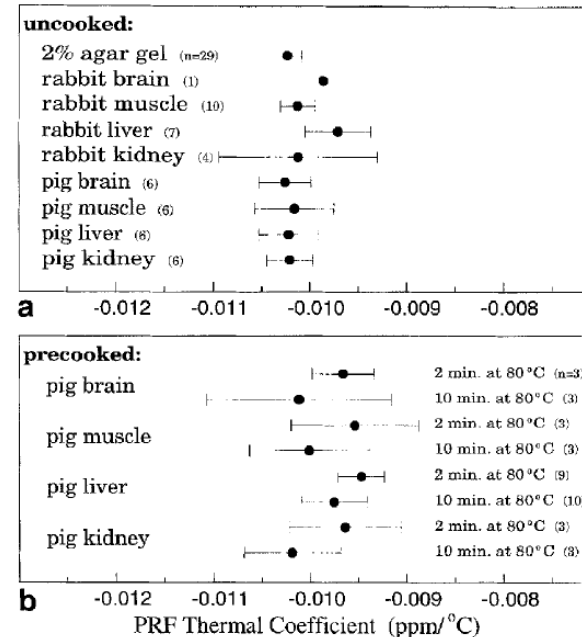


FIG. 7. PRF-thermal coefficients of (a) uncooked and (b) pre-cooked *ex vivo* rabbit and pig tissues obtained from this particular experimental arrangement. The error bars indicate a 95% confidence interval for an estimate in the mean using the Student's *t* distribution. Only one data point was acquired for rabbit brain.

\* Adipose tissue does not exhibit PRFS temperature dependence. (No H-bonds.)

Figure 1 source:

Hindman JC. Proton resonance shift of water in gas and liquid states. *J Chem Phys* 1966;44:4582-4592.

Figure 7 source:

Peters RD, Hinks RS, Henkelman RM. Ex vivo tissue-type independence in proton-resonance frequency shift MR thermometry. *Magn Reson Med* 1998;40:454-459.

# IMAGE PHASE

Small Change In  
Larmor  
Frequency



Change In MR  
Image Phase

$$\Delta\omega$$

$$\Delta\phi$$

2D MR Image

$$S(x, y) = |S(x, y)| e^{i\phi(x, y)}$$

# PRFS THERMOMETRY

$$\Delta\phi = \Delta\phi_T + \Delta\phi_b$$

Phase change due to other factors:  
(B0 Drift, Respiratory & Cardiac  
Motion, etc.)

Temperature induced phase change

## PRFS assumptions:

- Region doesn't contain fat.
- $\Delta\phi_b = 0$

$$\Delta\phi = (\gamma\alpha B_0 t_e) \Delta T$$

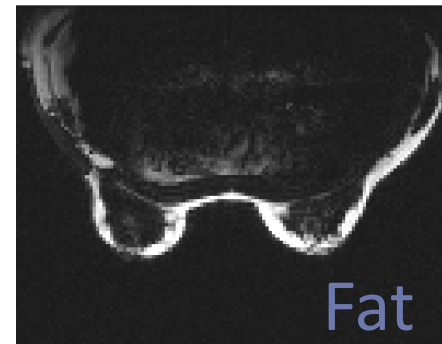
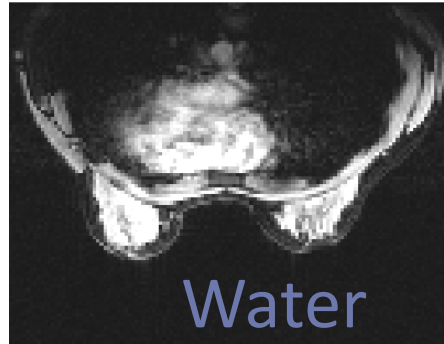
MR Image Phase Change

Linear Scaling Term

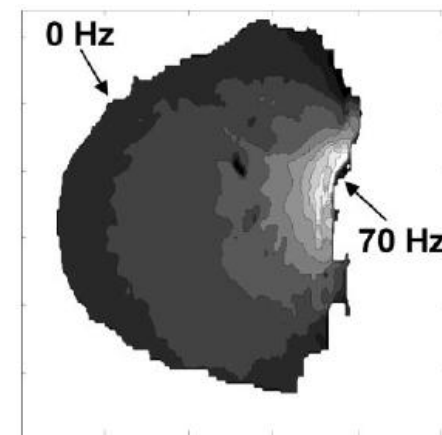
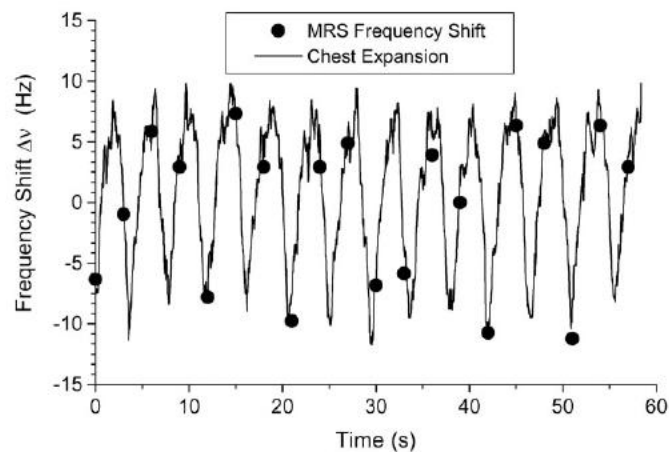
Temperature Change

# VALID ASSUMPTIONS?

- Regions of Interest often contains fat



- Phase change (not due to temperature change)



# FAT-REFERENCED THERMOMETRY

- Key Concept:
  - Phase of water does change with temperature
  - Phase of fat does not change with temperature

## Water Phase Change

$$\Delta\phi_w = \Delta\phi_T + \Delta\phi_b$$

## Fat Phase Change

$$\Delta\phi_f = \Delta\phi_b$$

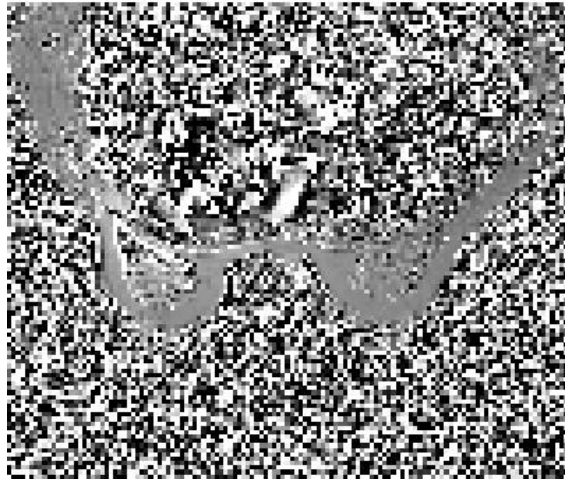
Isolate temperature dependent phase component

$$\Delta\phi_T = \Delta\phi_w - \Delta\phi_f$$

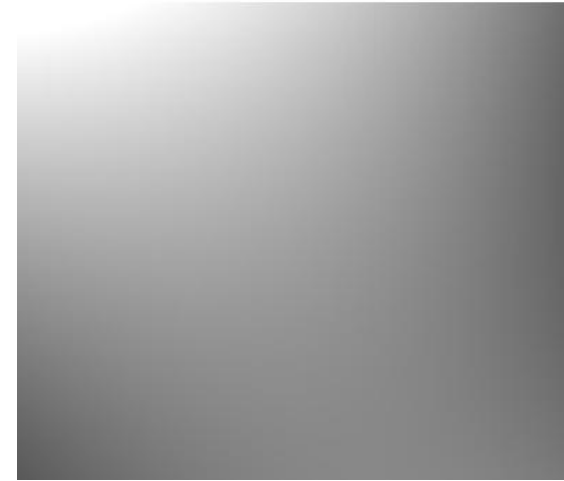
What if fat is not present in every pixel?

# WEIGHTED LINEAR LEAST SQUARES (1)

$$\Delta\phi_f(x, y)$$



$$\Delta\hat{\phi}_b(x, y)$$



$$\Delta\hat{\phi}_b(x, y) = a_0 + a_1x + a_2y + a_3x^2 + a_4y^2 + a_5xy$$

# NON-CONTACT THERMOMETRY

## MR Thermometry

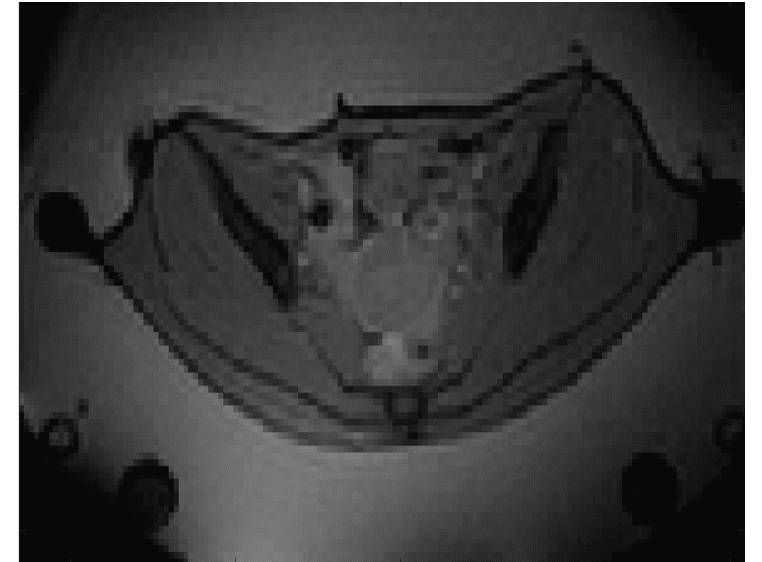
- With PRFS thermometry, 3D temperature change can be measured.

### Advantages

- 3D temperature distribution
- Non-invasive

### Disadvantages

- Differential method which susceptible to confounders such as motion
- Can only be used to measure temperature change in water rich tissue e.g. muscle
- Relative values instead of absolute values
- Slow measurements



VilasBoas-Ribeiro, et al.,  
*Medical Physics* (2022).

# NON-CONTACT THERMOMETRY

## T<sub>1</sub> based MR Thermometry

With PRFS thermometry, temperature measurements in fatty tissue is not possible.

Longitudinal relaxation time of the tissue is temperature dependent

$$T_1 \propto e^{-Ea(T_1)/kT}$$

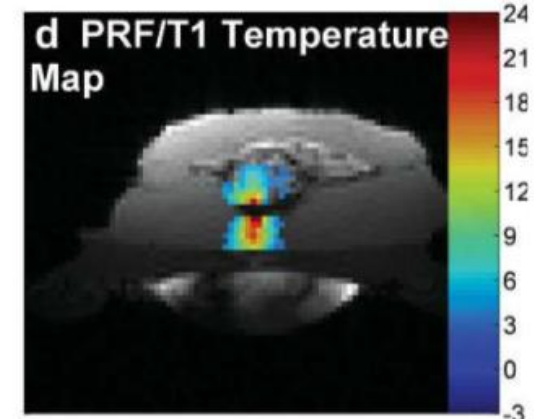
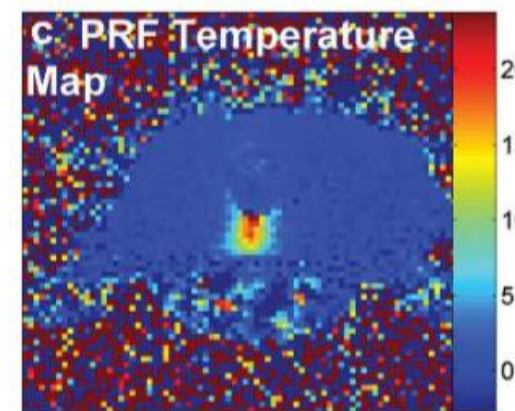
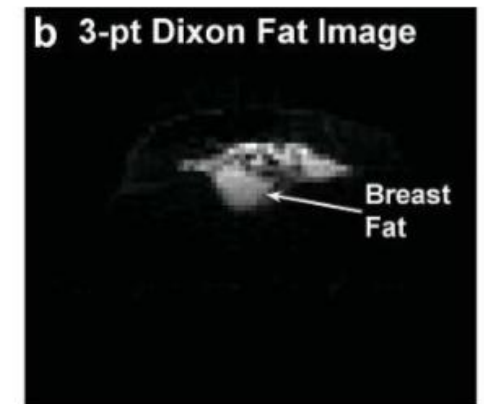
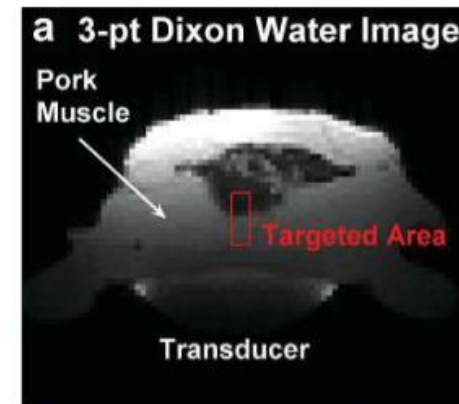
The signal change due to change in T1 can be used to monitor the temperature change.

### Advantages

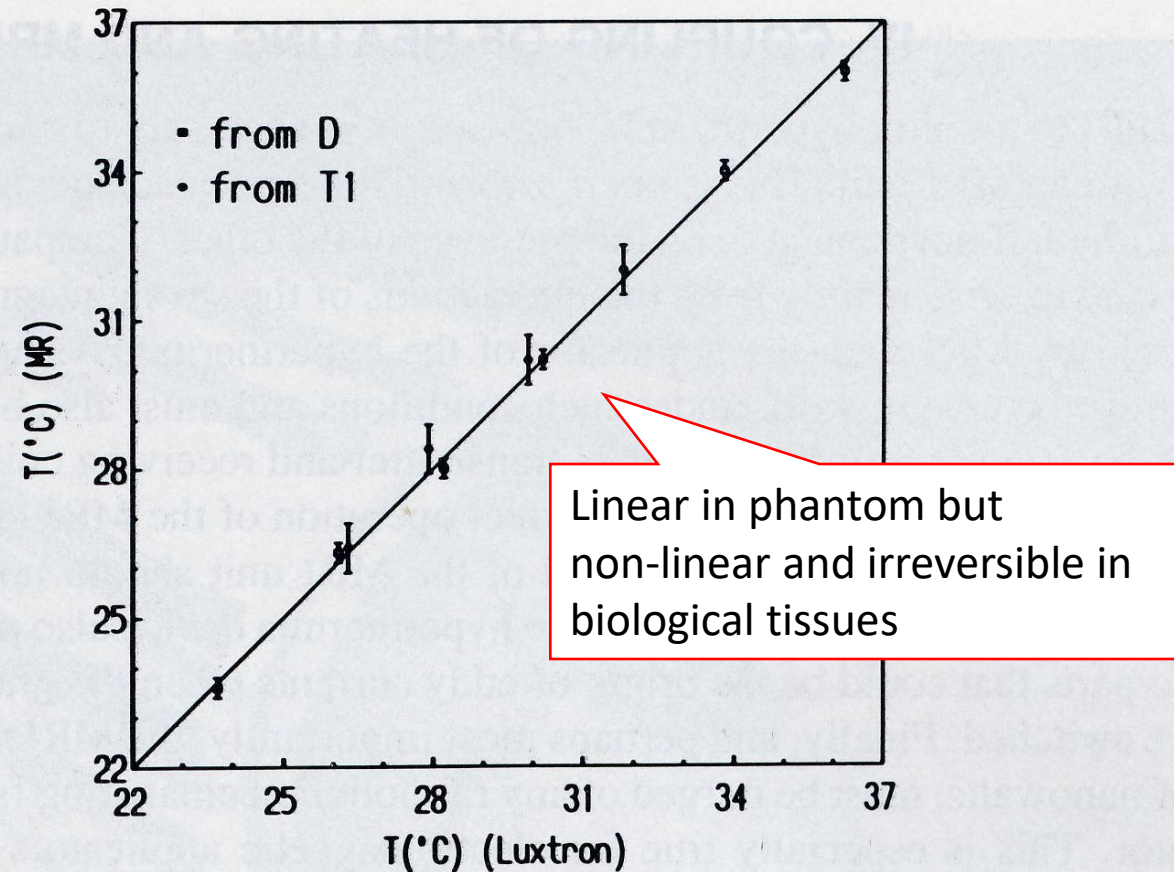
- Can measure in fatty tissue

### Disadvantages

- Low sensitivity
- Tissue dependency
- Slow



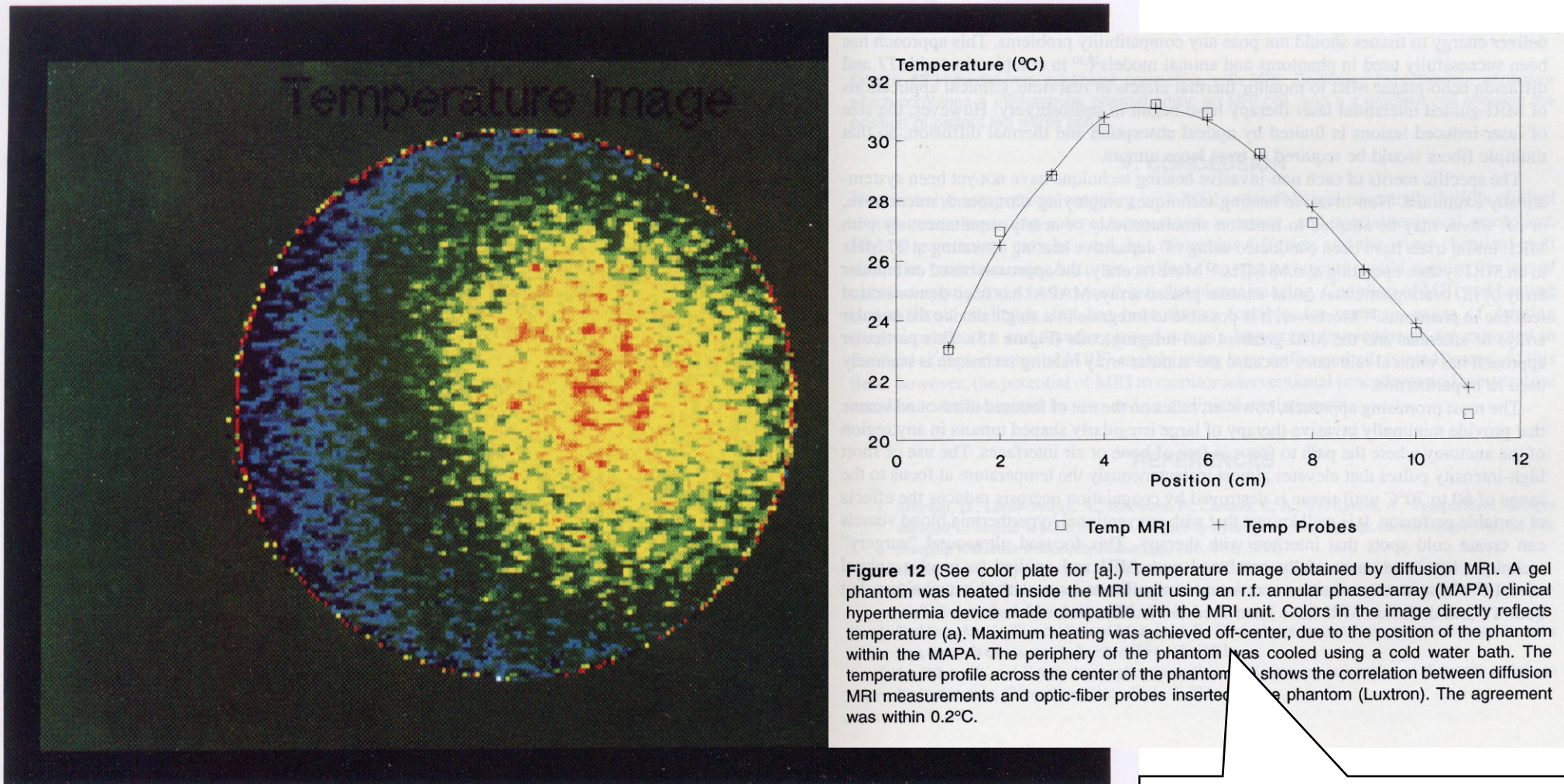




**Figure 11** Comparison of  $T_1$  and  $D$  in temperature measurement by MRI. Correlation of temperature, as measured with diffusion and  $T_1$  MRI, and optic fiber probes (Luxtron) in a polyacrylamide gel phantom. The predicted temperatures were found to be within 0.2 and 0.5°C of the probe measurements, respectively, using  $D$  and  $T_1$ .

LeBihan, 1988

## MRI: Diffusion



**Le Bihan, Figure 12:** (a) Maximum heating was achieved off-center, due to the position of the phantom within the MAPA. The periphery of the phantom was cooled using a cold water bath.

**Works great in phantom  
But ...**

# SUMMARY

Any property that shows temperature dependency can be used to measure temperature.

Thermometry methods could be divided into two groups 1) Methods that require contact 2) Contactless methods

Thermocouples and fiber-optic probes are the most common ways to measure temperature during hyperthermia

IR camera and MRT are the most common contactless methods.

MR based methods provide 3D temperature measurement possibility but they are slow and susceptible to confounders.