Applications of Microwaves in Medicine

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Diagnostic application | *Therapeutic applications*

Look → *see*

Heat → *destroy*

Outline

- Introduction - why microwaves?
- Applications reviewed
- What facilitates recent progress
- Examples of diagnostic applications
- Examples of therapeutic applications
- Conclusions

Introduction

- Advantages of technology
  - Wide range of frequencies
  - Ability to focus the energy
  - Variety of simulation tools
  - Relatively low cost
  - Low if any health risk
- Human characteristics
  - Differences in tissue properties (normal/tumor)
- Limitations of technology
  - Spatial resolution
  - Penetration depth
  - Electromagnetic interference
- Human characteristics
  - Complex patterns of fields in the body, scattering
  - Individual anatomical differences

Applications

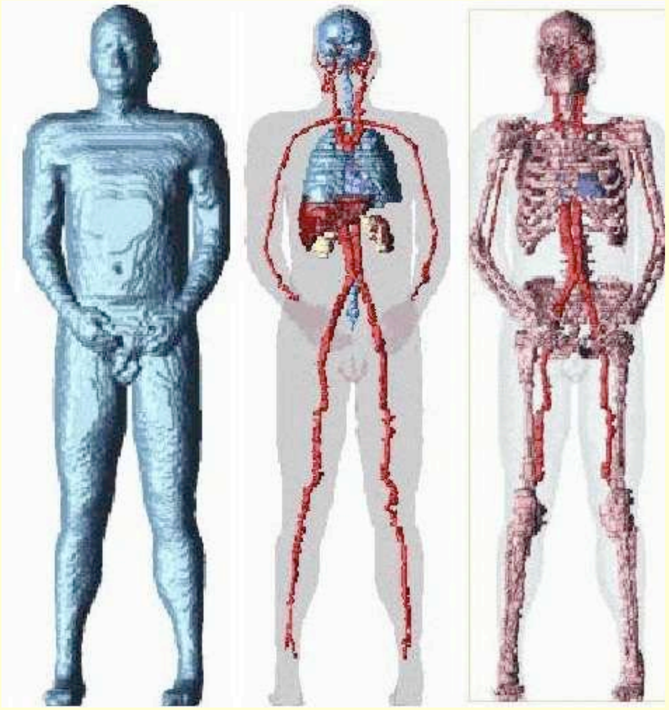
- Frequencies 100 MHz -30 GHz.
- Diagnostic applications: tumor detection based on differences in tissue electrical properties.
- Regional hyperthermia integrated with MRI
- Therapeutic applications based on local heating: prostate hyperplasia, heart and other tissue ablation, angioplasty.
- Applications not reviewed: MRI (& fMRI), radiometry, telemetry, motion detection.

Recent progress

- Advanced human body models
- Numerical techniques

FEM - finite element method, mostly in frequency domain, body parts represented by surfaces, volumes divided into tetrahedrons.
FDTD - finite difference time domain, voxel representation of body tissues.

- Computing facilities



Example of voxel body model used for FDTD computations

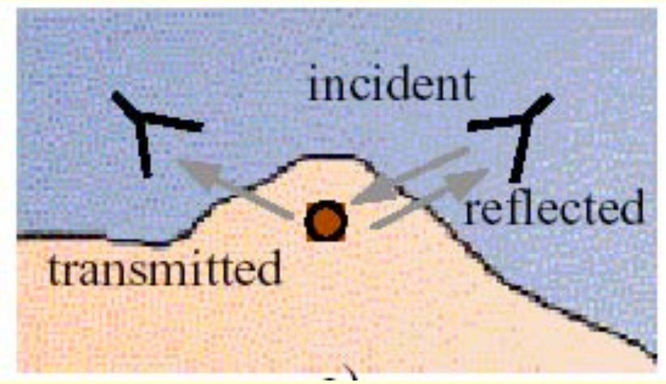
Diagnostic applications

- Based on contrast in dielectric properties
  - Most tumors 10 - 20 % difference
  - Breast tumors may have 2 + times difference
- Breast tumor detection potentially attractive
- Mammography (X-ray) - “the gold standard”
  - Screening may miss up to 15% of cancers; false positive - biopsies
  - Difficulty in imaging women with dense tissue
  - Concerns about screening young women
- Microwaves: Advantages
  - Electrical properties ??
  - Accessibility and low attenuation
  - Non-ionizing radiation

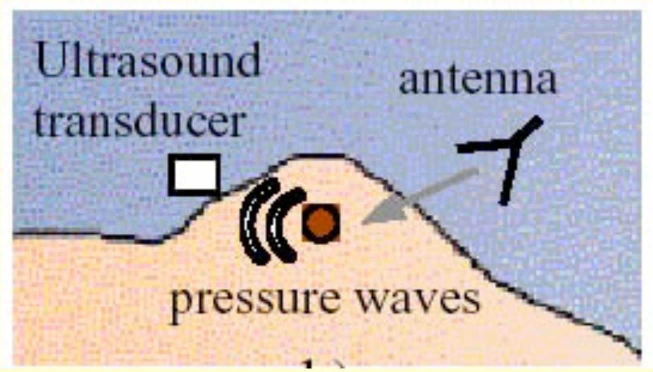
Limitations
- Electrical properties ??
- Heterogeneity (blood vessels, calcifications)

Microwave breast tumor detection

- Microwave tomography
  - – Inverse scattering, non-linear relationship between the acquired data and imagined pattern, non-unique solution.
  - – Early solutions - linear approximation, more recent accurate solutions based on optimization.



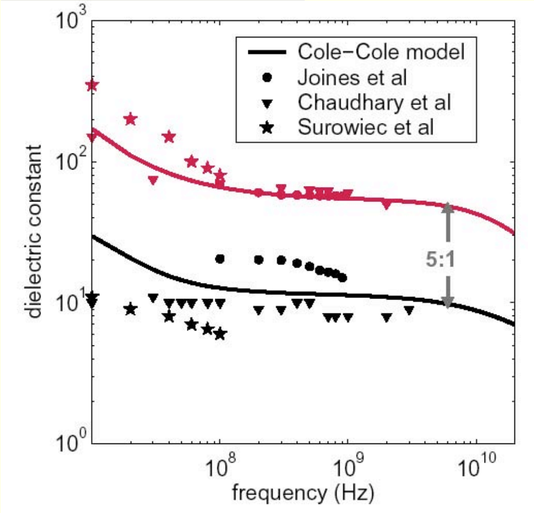
- Ultra-wideband microwave radar techniques
- Hybrid microwave - acoustic imaging

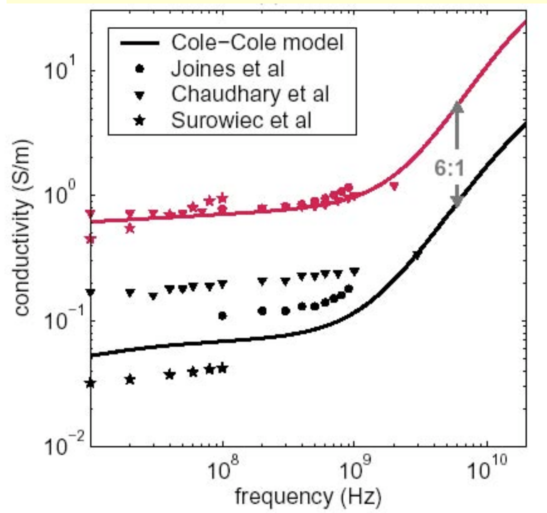


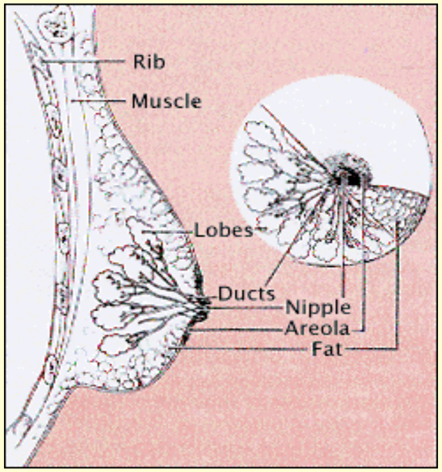
Breast tissue electrical properties

Early (before 2000) published data

- Are not all in agreement
- Limited sample sizes and frequency ranges
- Do not consistently distinguish between different normal tissue types







Source: Dr. S. Hagness, U. of Wisconsin

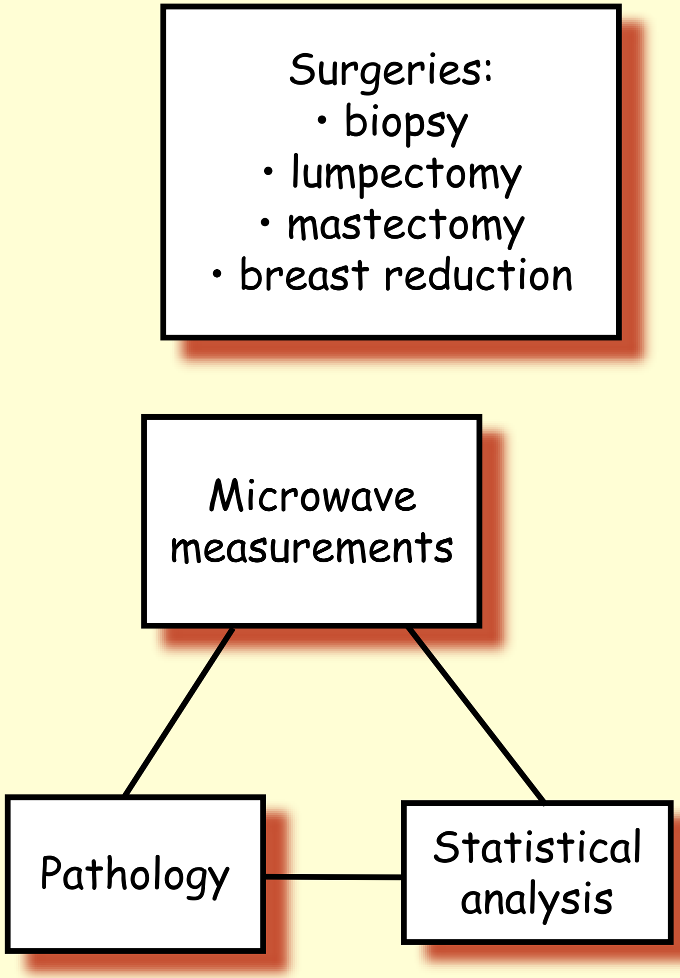
Breast tissue dielectric spectroscopy

- Comprehensive study to characterize malignant, benign, and normal breast tissues

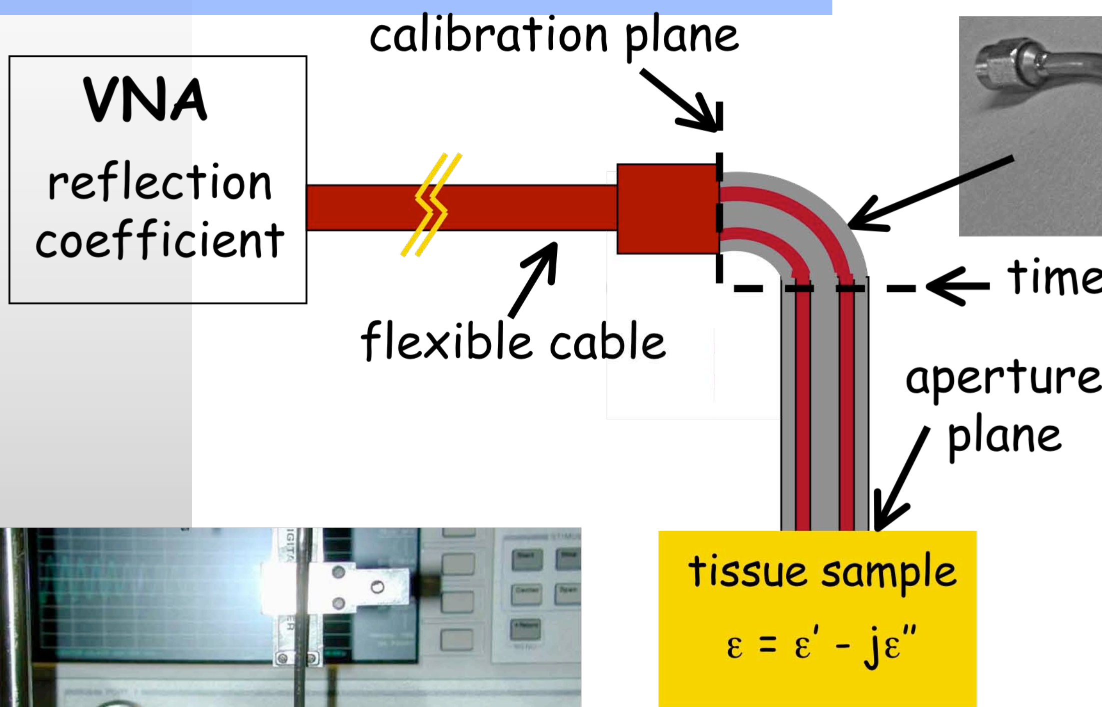
  U. Wisconsin-Madison (S. C. Hagness) and
  U. Calgary, Canada (M. Okoniewski)

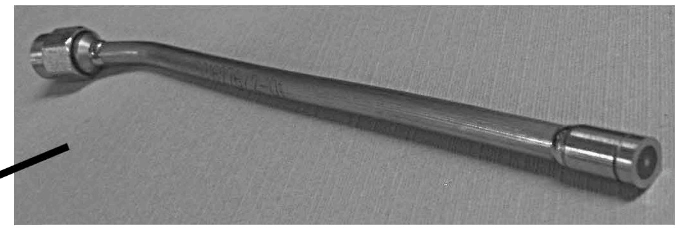
- Frequencies 0.5 - 20 GHz
- Total number of patients 93, samples 490; ages 17-65
- Tissue composition determined by pathologists

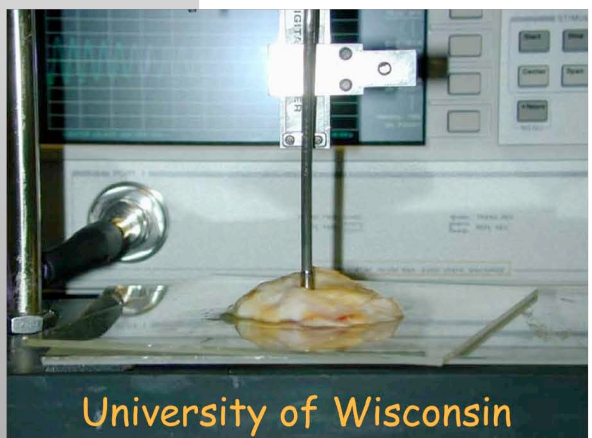
  Normal breasts: percentage adipose, fibrous connective, and glandular



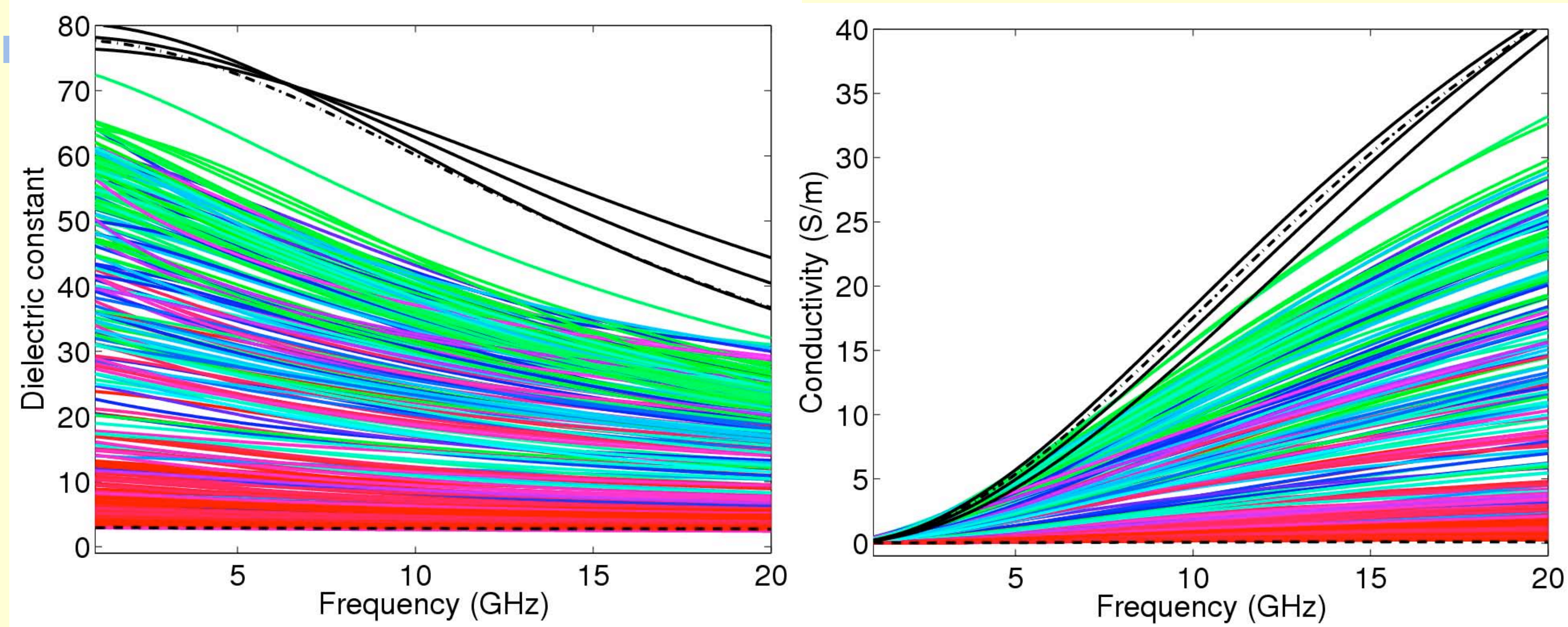
Breast tissue dielectric spectroscopy





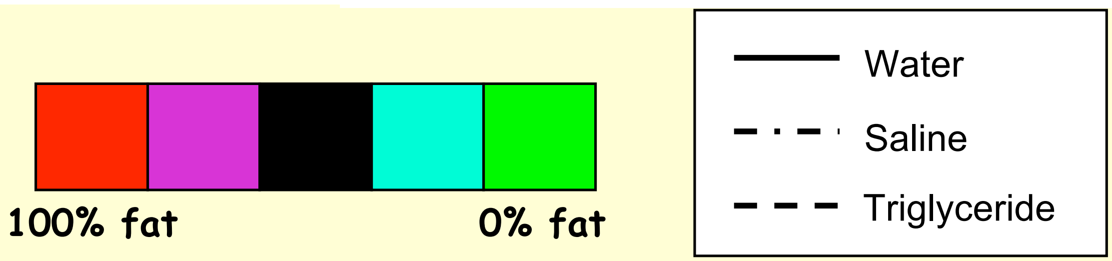


Results: normal breast tissue



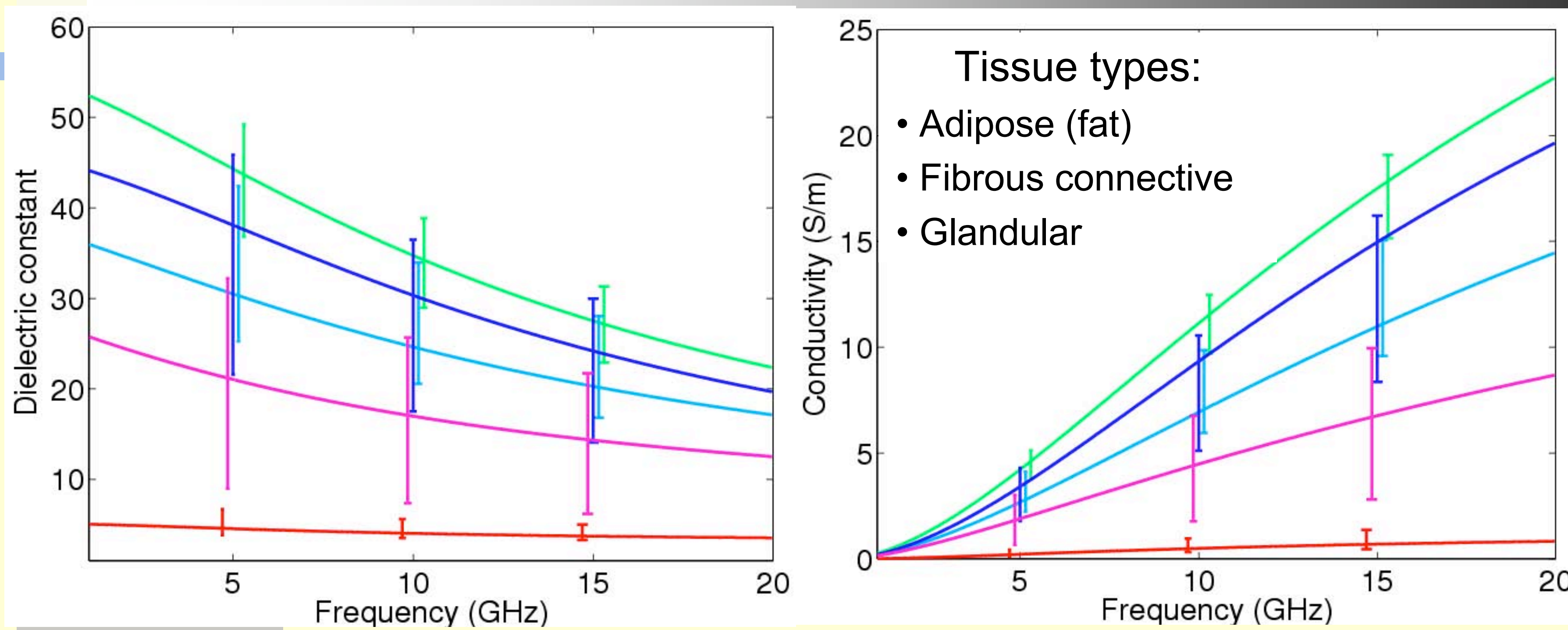
Tissue types:

- Adipose (fat)
- Fibrous connective
- Glandular



Source: Drs. Hagness & Okoniewski

Results: normal breast tissue



60-80% fat
20-40% fat

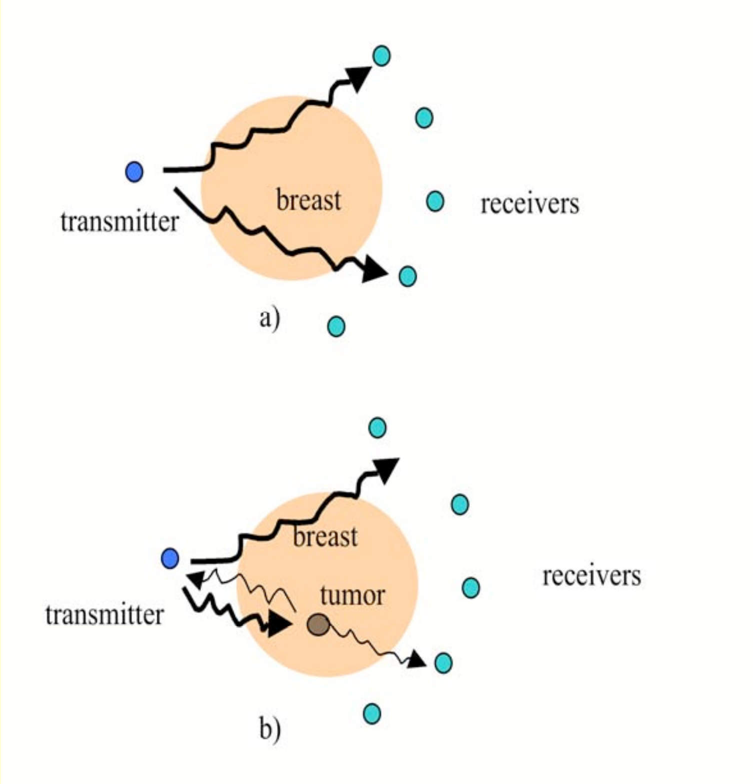
80-100% fat
40-60% fat
0-20% fat

Range bars (at 5, 10, 15 GHz):
25th-75th percentile
of parameter values

Source: Drs. Hagness & Okoniewski

Microwave Tomography

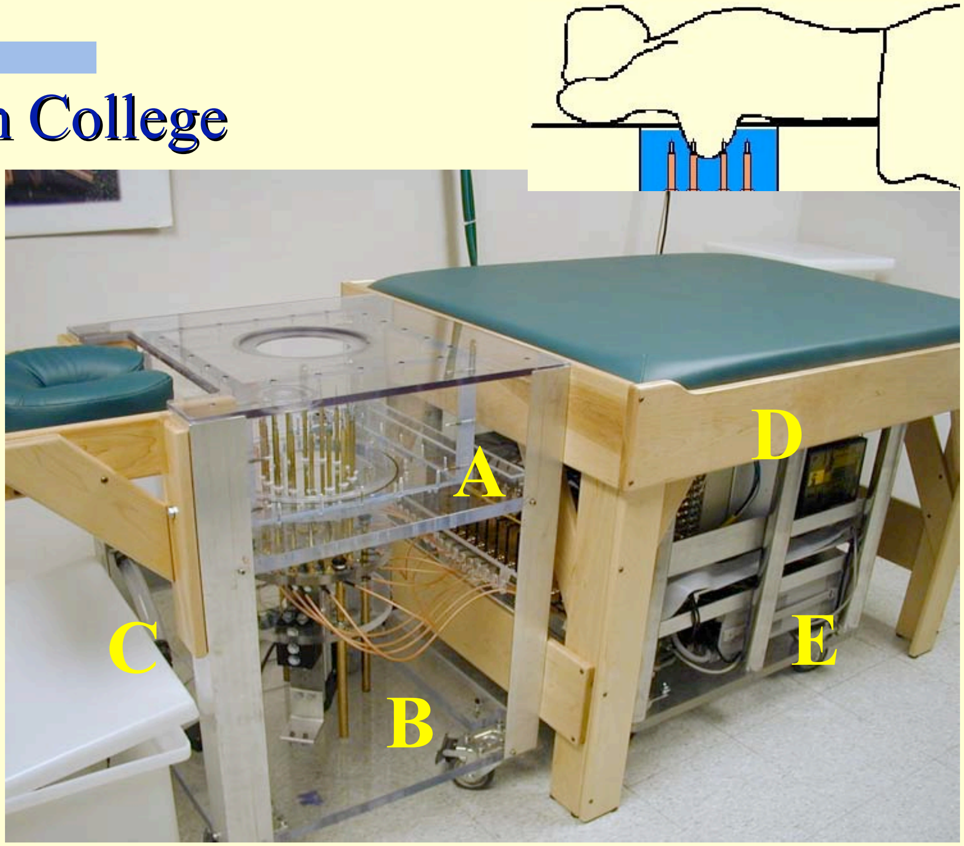
- Transmitted waves recorded at a number of locations; repeated for various transmitter positions
- Measured data compared to model
  - forward problem: material properties estimated, transmitted waves at the measurement points computed
  - forward problem solution and measurements compared
  - estimate of material properties updated and the process repeated till convergence



Microwave Tomography

Clinical test system at Dartmouth College

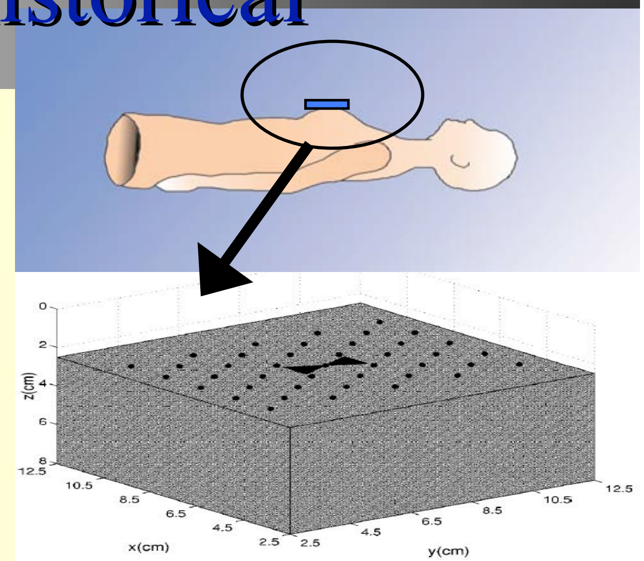
- Acquisition system - 32 well isolated channels.
- Monopole antennas
- Saline or glycerin/saline mixture coupled clinical interface.
- Multiple frequencies 0.3 - 0.9 GHz or 0.5 - 3 GHz (in development).
- FDTD forward calculations
- Gauss-Newton reconstruction using all frequencies simultaneously
- Exam 10 - 15 minutes.
- Resolution 1 cm.
- Dynamic range 130 dB



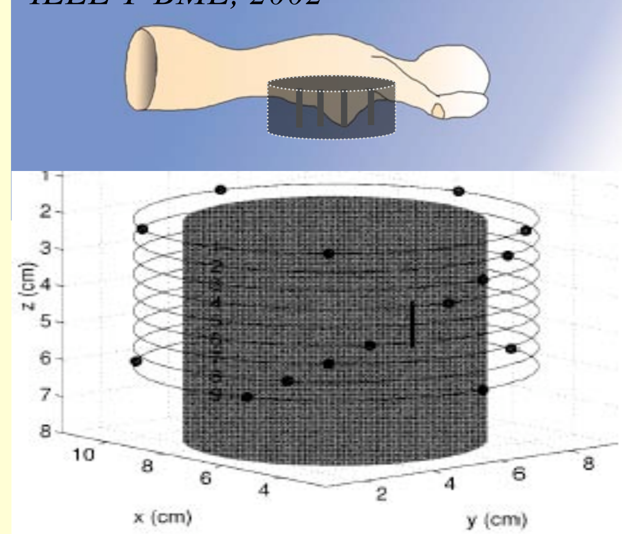
(A) Microwave illumination tank; (B) Antenna motion actuator; (C) the coupling medium reservoir; (D) Patient examination table; and (E) Electronics cart.

UWB radar-based detection - historical

- **1998/1999**: S. C. Hagness, A. Taflove & J. Bridges (Northwestern U.): concept proposed and demonstrated with FDTD models of planar antenna array system
- **2000**: E.C. Fear & M.A. Stuchly (U. Victoria): cylindrical system, skin subtraction - FDTD
- **Today**: two main groups pursue simulations & experiments
  - Susan C. Hagness, U. Wisconsin
  - Elise C. Fear, U. Calgary
  - Other groups



Source: Fear, Li, Hagness, Stuchly, IEEE T-BME, 2002



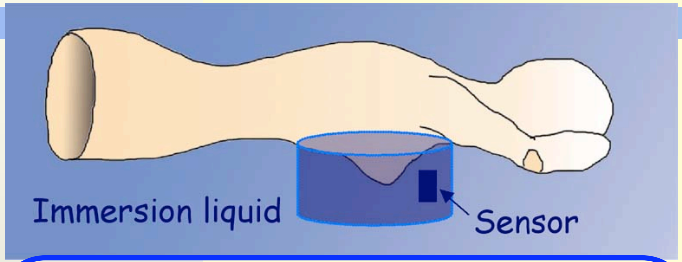
Radar-based detection - basics

- Ultra-wideband pulse: modulated Gaussian or frequency contents optimized (1 - 10 GHz)
- Small broadband antennas
- Signal processing
  - *Calibration:* removal of the antenna artifacts
  - *Skin surface identification and artifact removal:* reduce dominant reflection from skin - various algorithms
  - *Compensation:* of frequency dependent propagation effects
  - *Tumor detection*

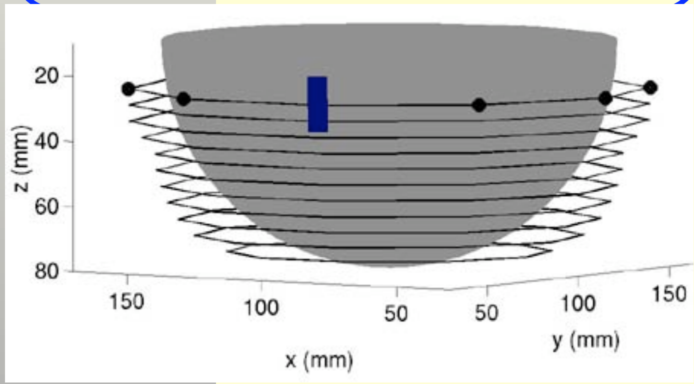
    Basic algorithm: **compute time delays from antennas to focal point, add together corresponding signals, scan focal point through volume**

    Additional **complex signal processing**

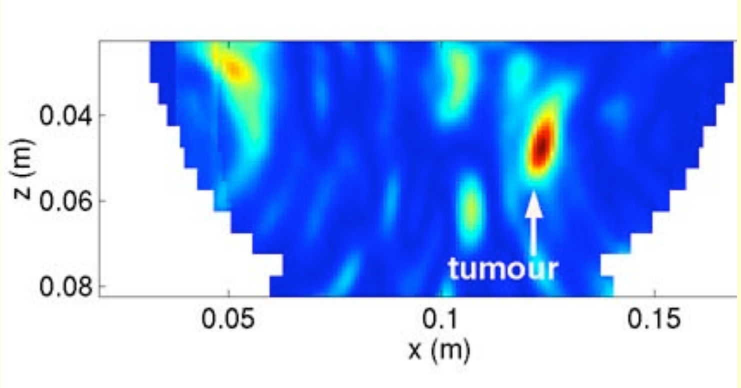
Tissue Sensing Adaptive Radar (TSAR)



Data collection:
skin sensing scan
tumor detection scan

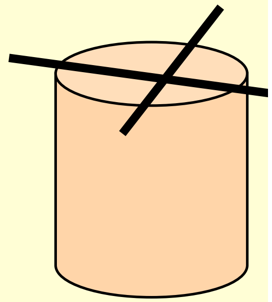


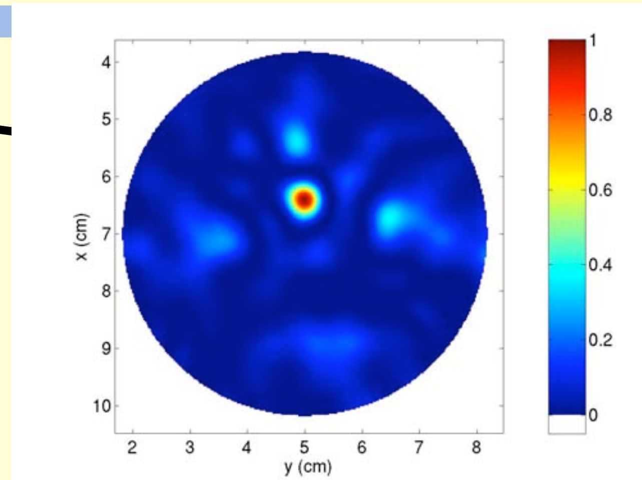
TSAR algorithm:reduce clutter
(e.g. identify skin reflection, estimate and subtract, repeat in breast interior)
focus to create image



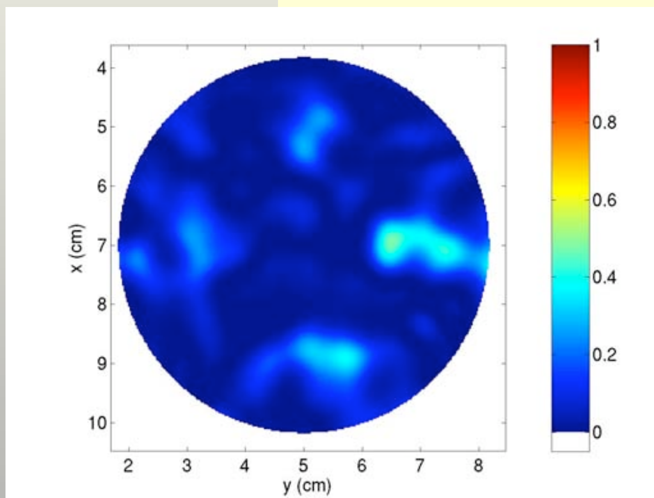
Source: Elise Fear, University of Calgary

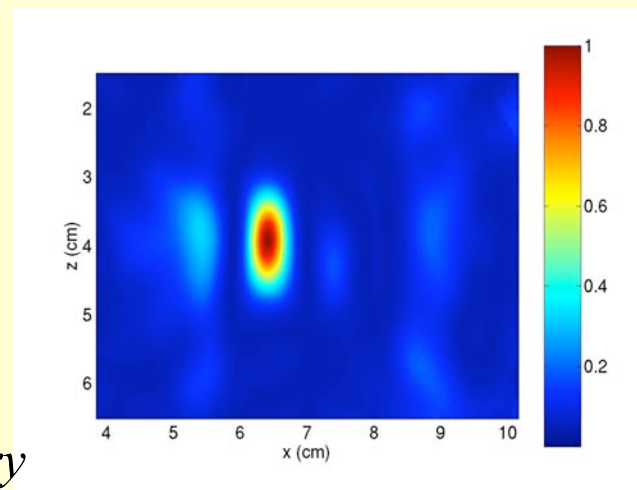
Time space adaptive radar (TSAR): 3-D localization





Without tumor

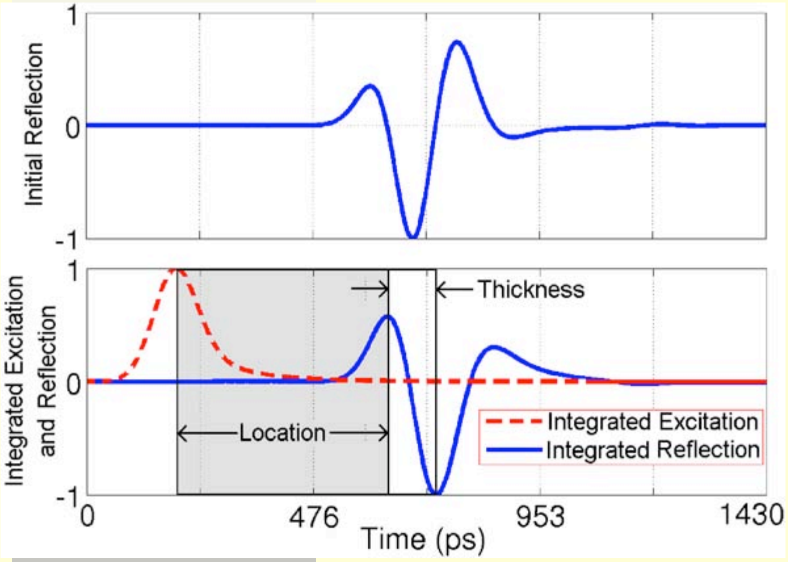




Source: Elise Fear, University of Calgary

TSAR: skin sensing& reflection removal

Early method peak detection



skin location error: <1 % to 2 % ,
thickness error: ~3 % to >160 %
- as skin thickness drops from 3 to 1mm

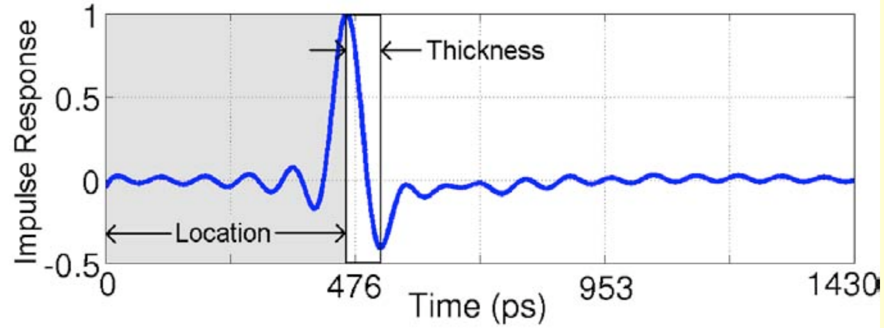
Source: Elise Fear, University of Calgary

Deconvolution method

Basic idea: $x(t) * h(t) = y(t)$

where $x(t)$: excitation (no scatterer present)
$h(t)$: impulse response of the system
$y(t)$: calibrated received signal.

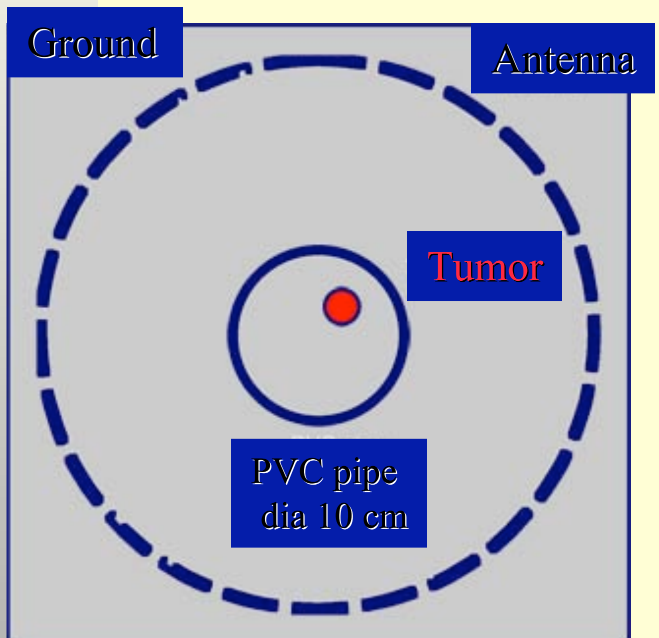
If a good estimate of $h(t)$ is obtained, then more accurate information on the model is expected.

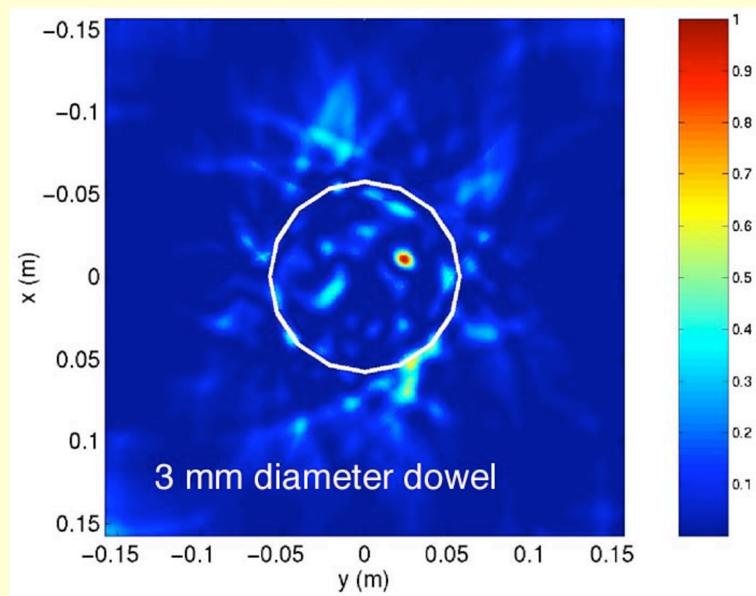


skin location error: fraction of %,
thickness error: a few to 20 %
for skin thickness 1 - 2 mm

TSAR: First Generation Experiment

- Basic method verification
- PVC pipe, wood and air to represent skin, tumor and fatty tissue

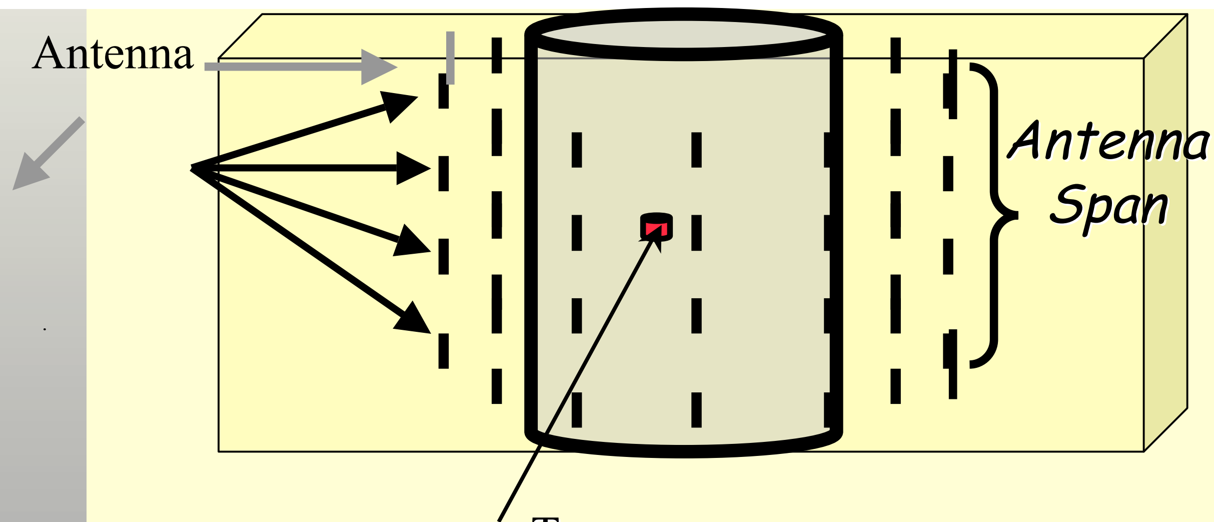




Source: Elise Fear, University of Calgary

TSAR: Second Generation

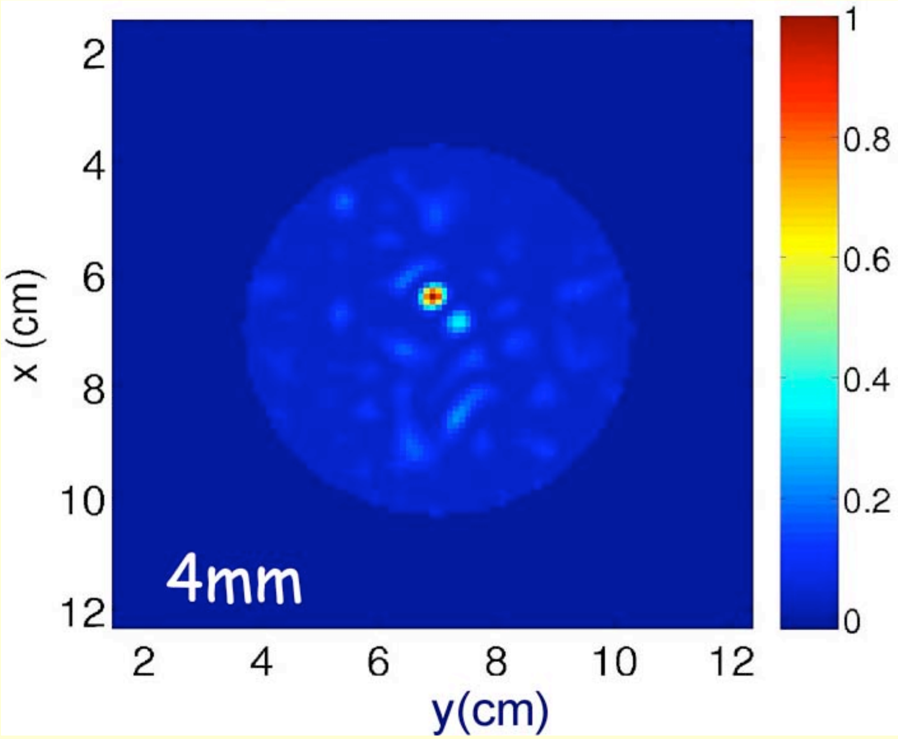
- Synthetic antenna array: one antenna scanned around cylinder, 10 locations to form a row; scan various numbers of rows
- Complex permittivity values for materials similar to skin $\varepsilon=36$, $\sigma=4$ S/m, breast tissue $\varepsilon=36$, $\sigma=0.4$ S/m, and tumor $\varepsilon=50$, $\sigma=4$ S/m
- Breast model immersed in matching liquid -search for the best liquid
- Three dimensional; breast 6.8 cm diameter, skin 2 mm thick



Source: Elise Fear, University of Calgary

Second generation TSAR

- Oil immersion medium optimal
- Small tumors detected



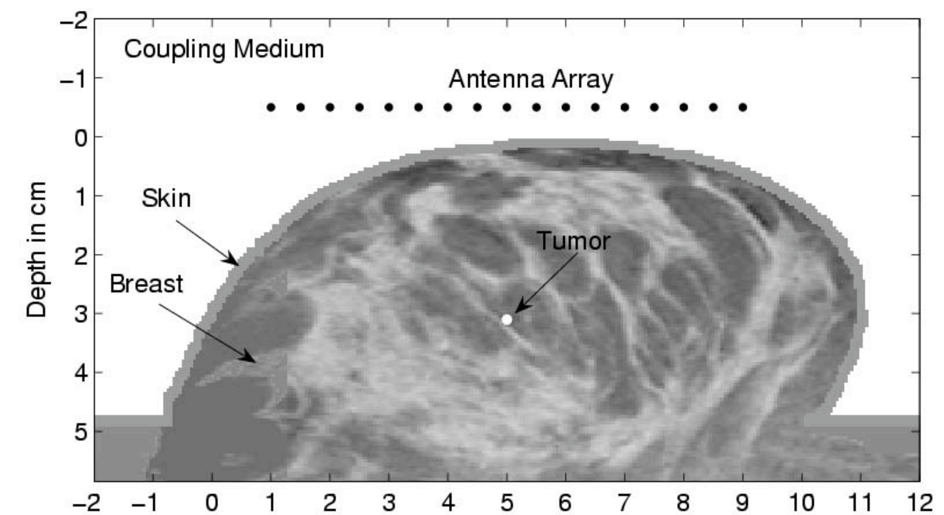
Source: Elise Fear, University of Calgary

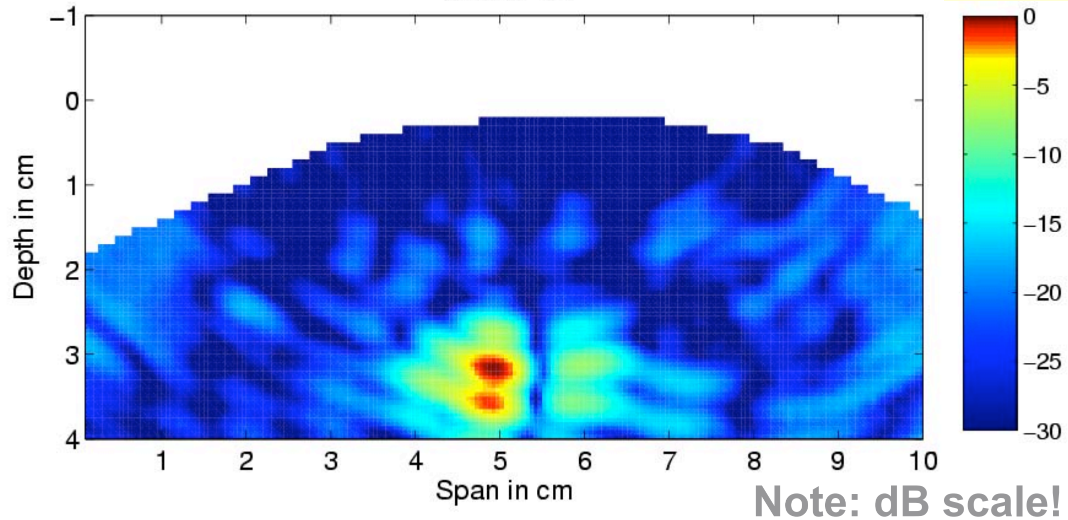
Microwave Imaging: University of Wisconsin

Source: Susan Hagness, University of Wisconsin

- **“Least-squares optimal” beam forming**
  - Creates image of backscattered energy
  - Compensates for frequency-dependent propagation effects
  - Achieves optimal suppression of clutter and noise
  - Robust with respect to uncertainties in normal tissue properties
- **Generalized likelihood ratio test (GLRT)**
  - Uses hypothesis testing to detect tumor
  - Creates image of test statistic
  - Offers potential to infer variety of tumor characteristics

University of Wisconsin: Results 2D



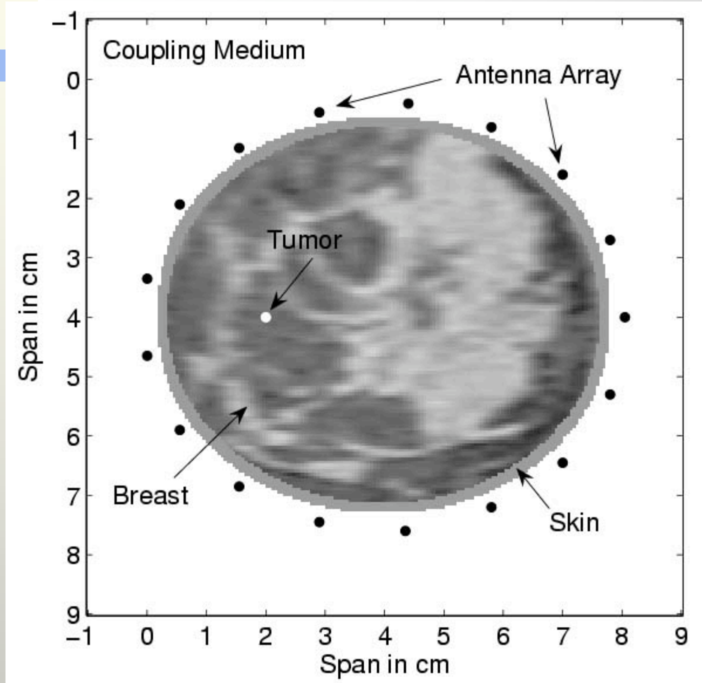


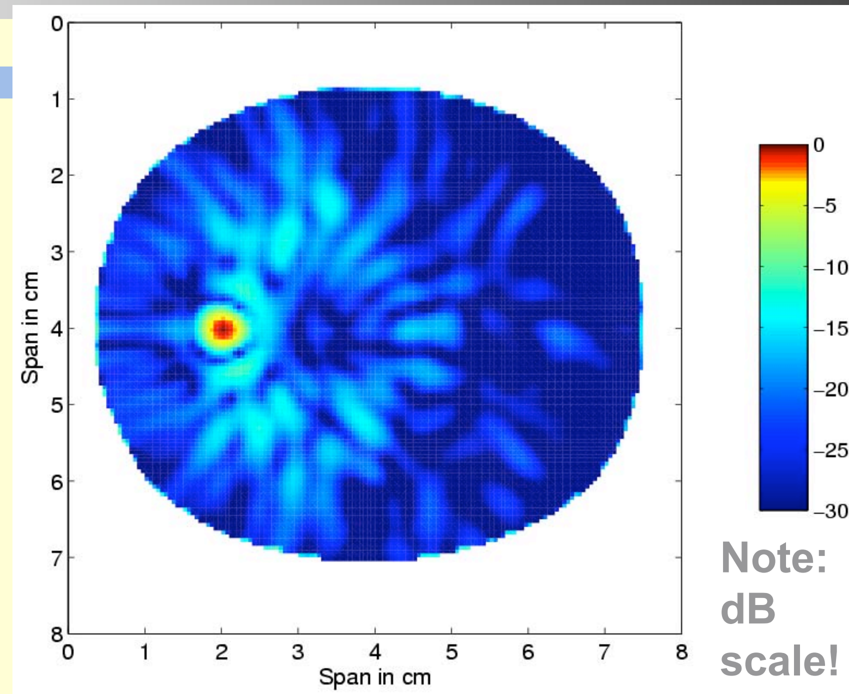
- MRI-derived 2D phantom (supine)
- tumor diameter: 2 mm
- dielectric contrast: ~5:1

Li, Bond, Van Veen, Hagness, *IEEE AP Magazine*, '05

- Pre-processing of backscattered signals:
  1) breast surface identification
  2) skin-artifact removal
- Signal-to-clutter ratio: ~16 dB

University of Wisconsin: 2D Results





Note: dB scale!

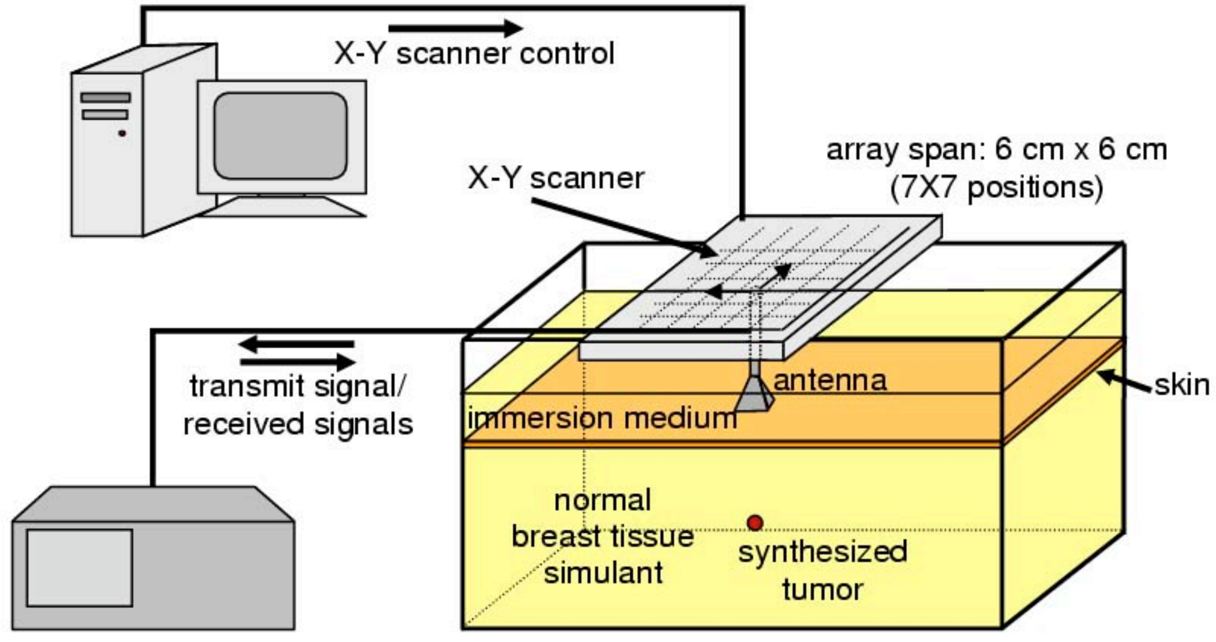
- MRI-derived 2D phantom (prone)
- tumor diameter: 2 mm
- dielectric contrast: ~5:1

- Pre-processing of backscattered signals:
  1) breast surface identification
  2) skin-artifact removal
- Signal-to-clutter ratio: ~20 dB

Li, Bond, Van Veen, Hagness, *IEEE AP Magazine*, '05

UW-Madison Experiment (1^{st}-Generation)

- Compact UWB antenna scanned to synthesize 2D planar array (7 x 7 elements)
- Tissue and tumor properties contrast similar to actual
- Immersion medium: soybean oil
- Data acquisition: swept-freq S11, converted to time-domain pulses



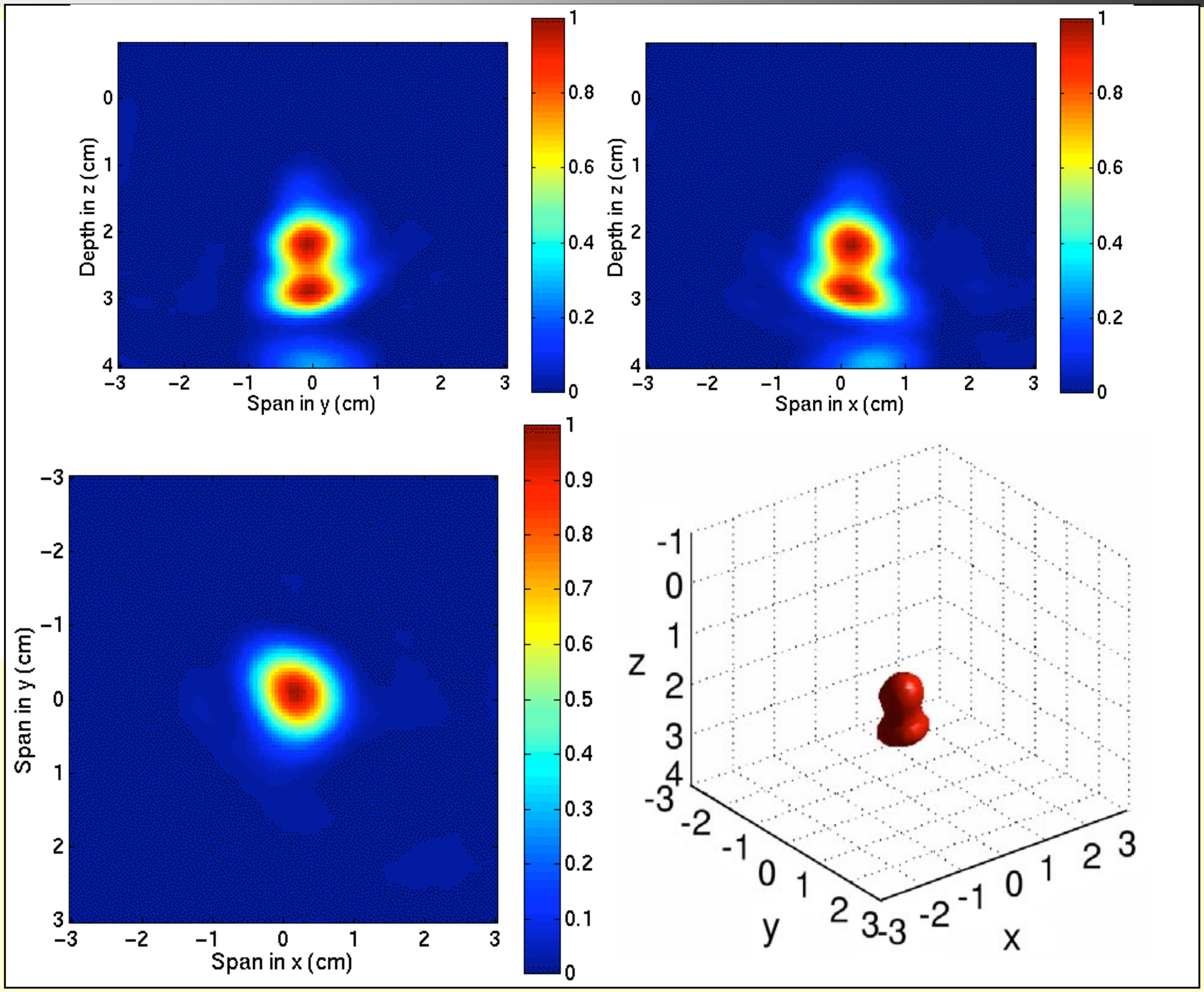
Li et al, *IEEE T-MTT,* ’04

U. Of Wisconsin: Experimental results

Tumor diameter:
4 mm

Tumor depth:
2 cm below skin

Dielectric contrast:
1.5:1



Li et al, *IEEE T-MTT, '04*

Breast tumor detection: summary

- Important and appealing application
- Promising results
  - algorithm development
  - preliminary experiments
  - many research groups
  - reliable data for electrical properties available
- Contrast in electrical properties of tumor compared to various healthy tissues may be less than anticipated

Therapeutic applications

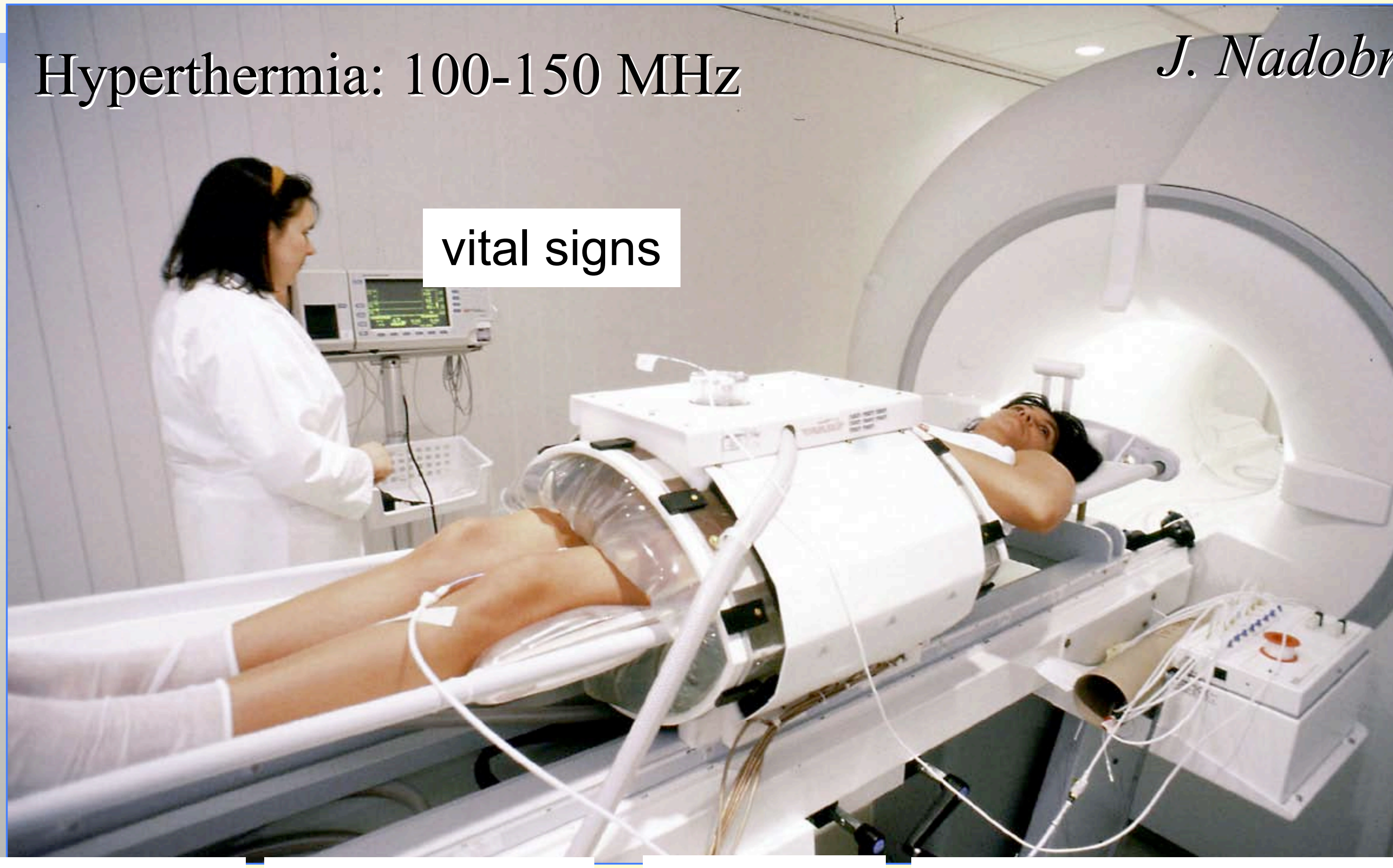
- Developed since 1960s
- Temperature monitoring & control (closed feedback loop) important but not easy
- Regional hyperthermia
  - integrated systems (MRI + microwaves)
  - superficial antenna arrays (also conformal) + radiometry
- Localized heating
  - prostate hyperplasia (commercial systems)
  - ablation (heart, liver, cornea, esophagus)
  - angioplasty

Integrated regional hyperthermia systems

- RF hyperthermia applicators + MRI for temperature monitoring
- Two groups
  - –ZIB in Berlin, Germany
  - –University Medical Center, Utrecht, Holland
- Antenna arrays
- Optimization based on temperature

Hyperthermia & MRI System at ZIB Berlin

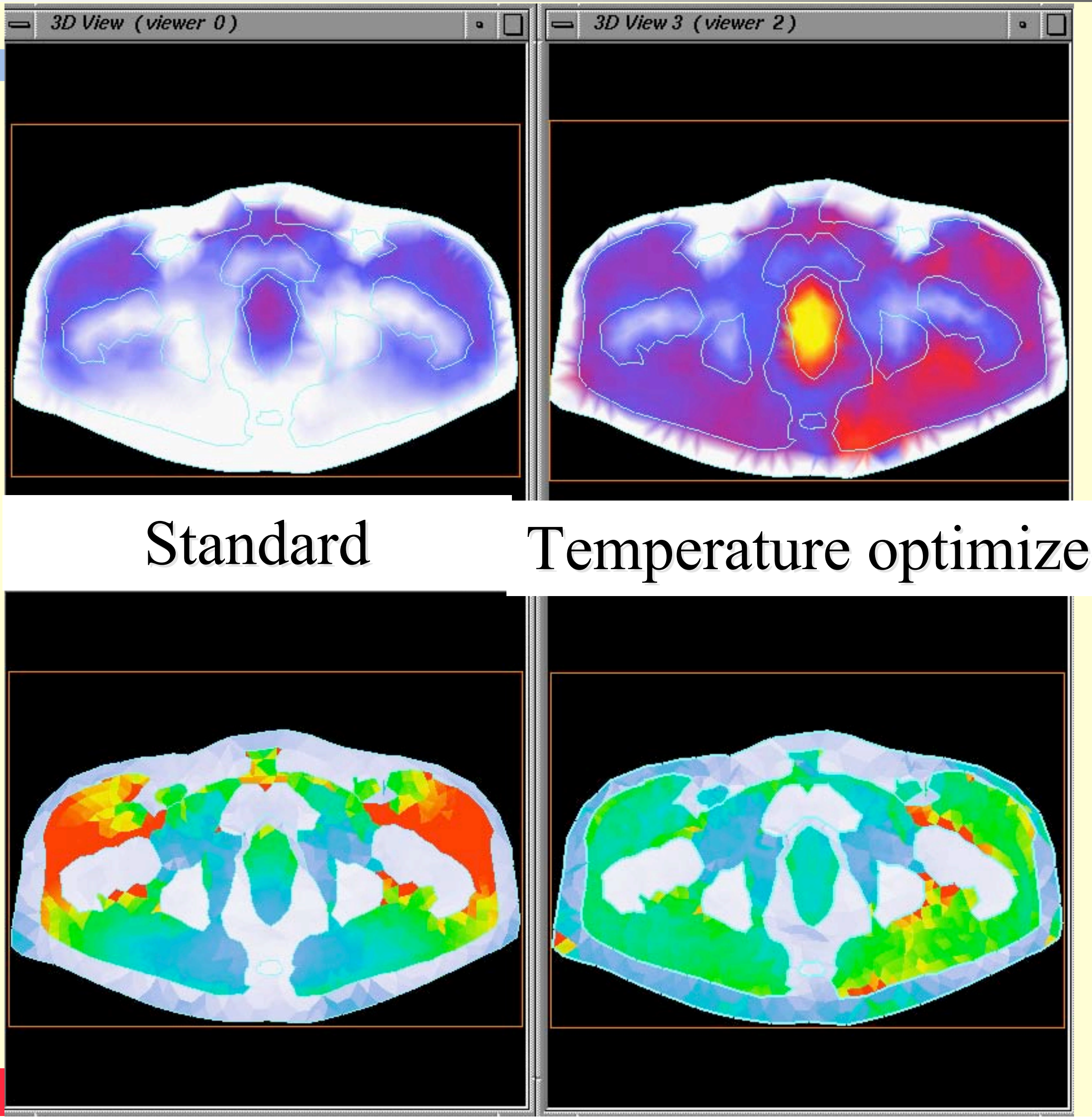
J. Nadobny et al



Hyperthermia at ZIB Berlin: SAR & temperature

Temperature

SAR

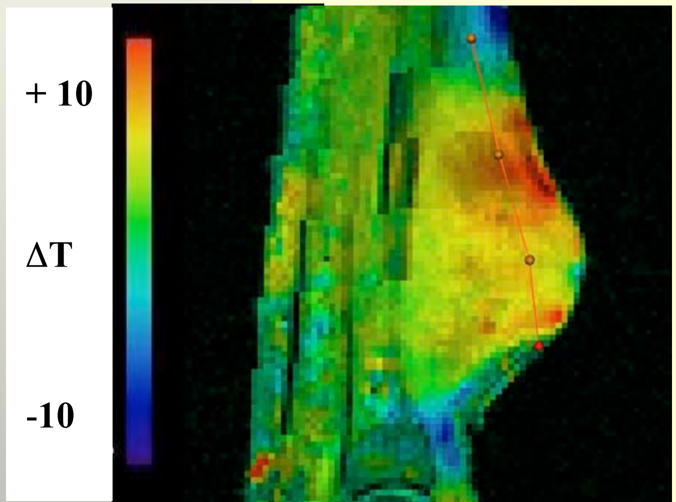


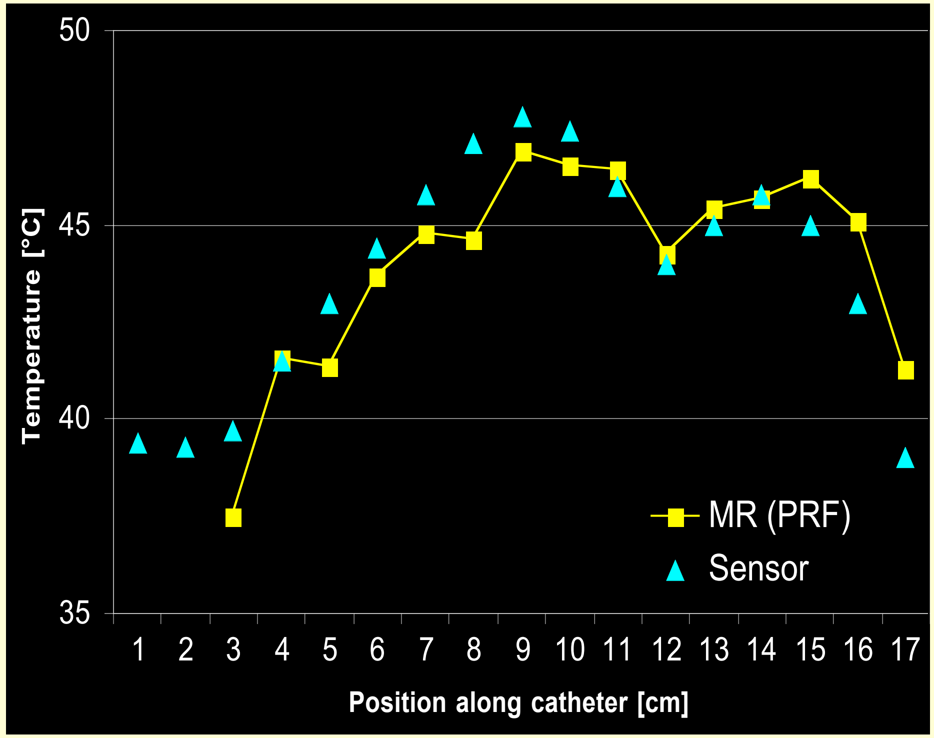
Standard

Temperature optimized

MRI & Sensor-measured temperature

Map of temperature increase





Nadobny et al, ZIB, Berlin

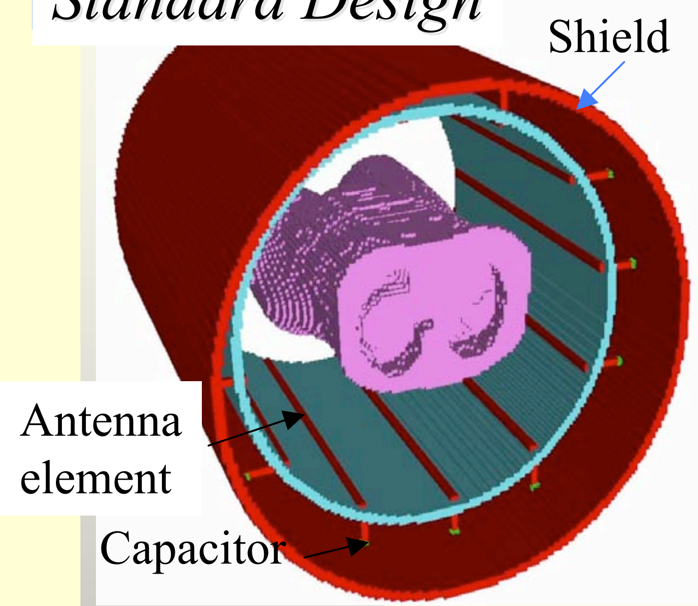
Utrecht Hyperthermia System

Jan Lagendijk et al

- 3 T MRI system, RF = 128 MHz
- Radio frequency within the range optimal for regional hyperthermia of abdomen
- Efficient 3T MRI requires tuned antenna array instead of traditional coils
- The same antenna array for hyperthermia and MRI monitoring
- Water (de-ionized) bolus
  - Optimal power coupling & surface cooling of the patient
  - Shorter antennas (more elements): better control of focus and uniformity of B field in imaging
  - No significant effect on S/N in imaging

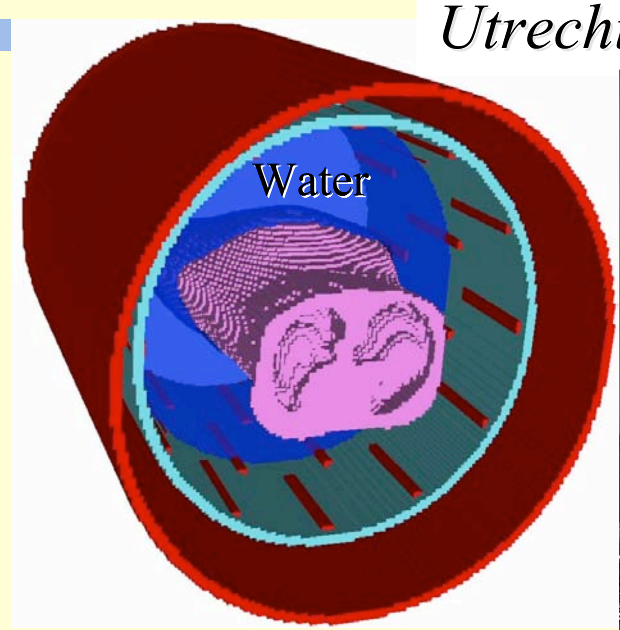
Standard 3T MRI & Utrecht Hyperthermia System

Standard Design



- Air: $\lambda/2 = 1.17$ m
- 12 antenna elements
- Elements resonant - external capacitors
- Each antenna can be excited separately

Utrecht System

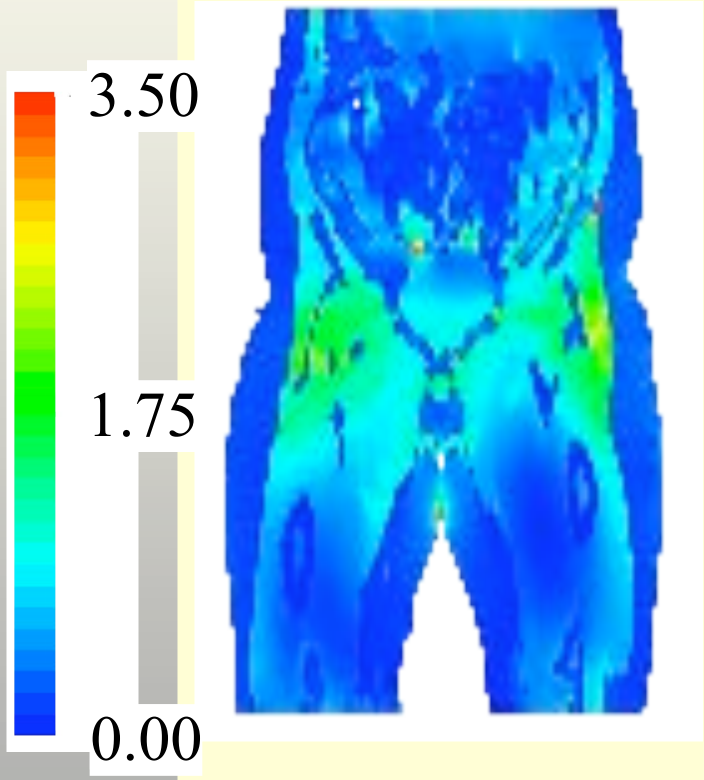


- Water: $\lambda/2 = 0.13$ m
- 3 rings of 12 antenna elements, each resonant
- Antennas (36) excited separately

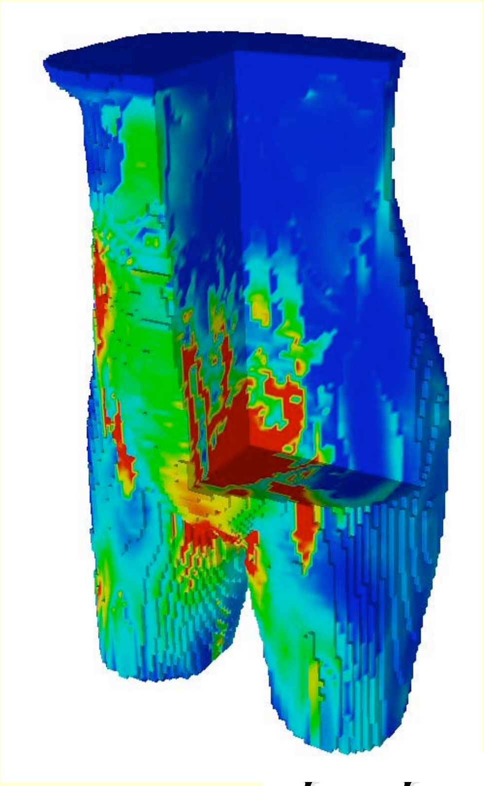
Jan Lagendijk et al

Utrecht Hyperthermia & MRI System

SAR - Imaging Mode



SAR - Hyperthermia Mode



SAR scale different

Jan Lagendijk et al

Utrecht Hyperthermia & MRI System

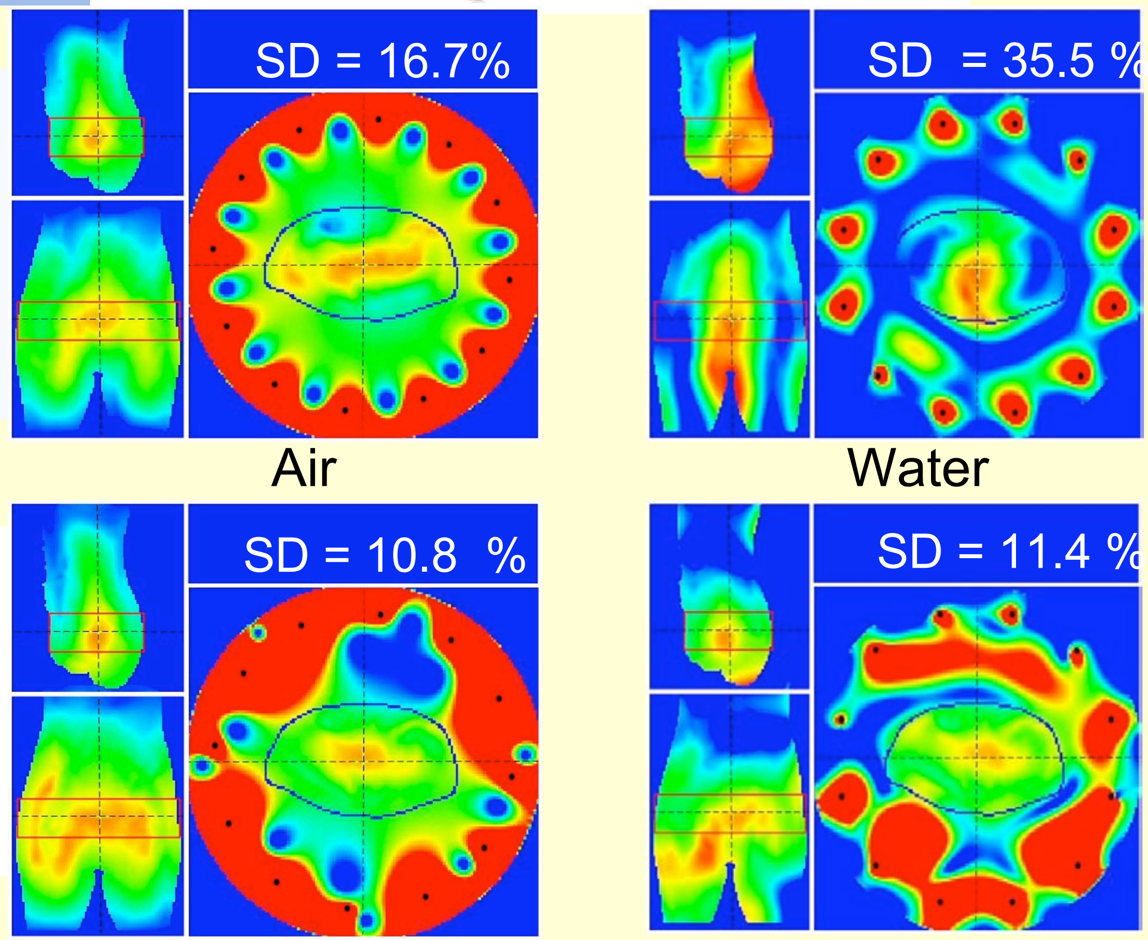
Results: MRI performance

Quadrature excitation

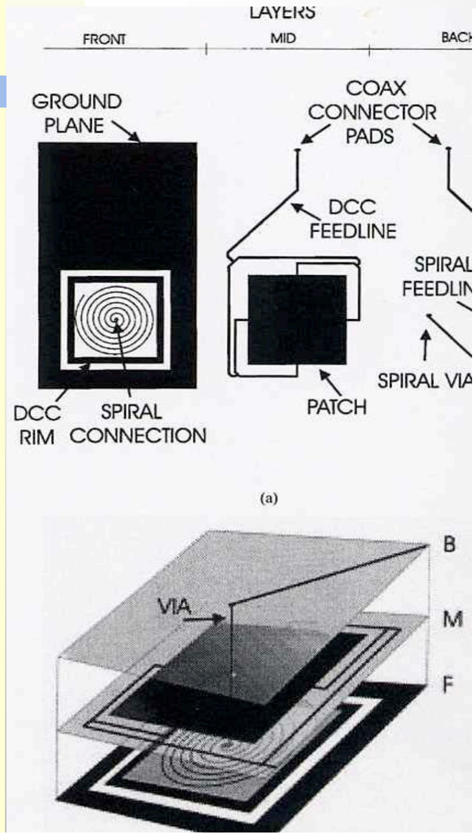
All antennas with the same amplitude and fixed phase shifts

Optimal settings

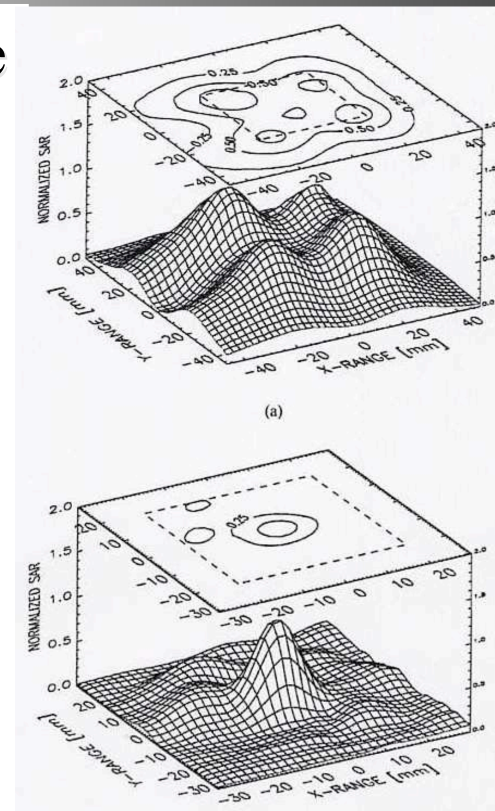
Computer optimized B-field homogeneity with amplitude and phase steering



Hyperthermia therapy - superficial



- Conformal, thin, flexible applicator for superficial heating (chest wall carcinoma, melanoma, residual disease after tumor excision, plaque psoriasis).
- Annular ring used for heating.

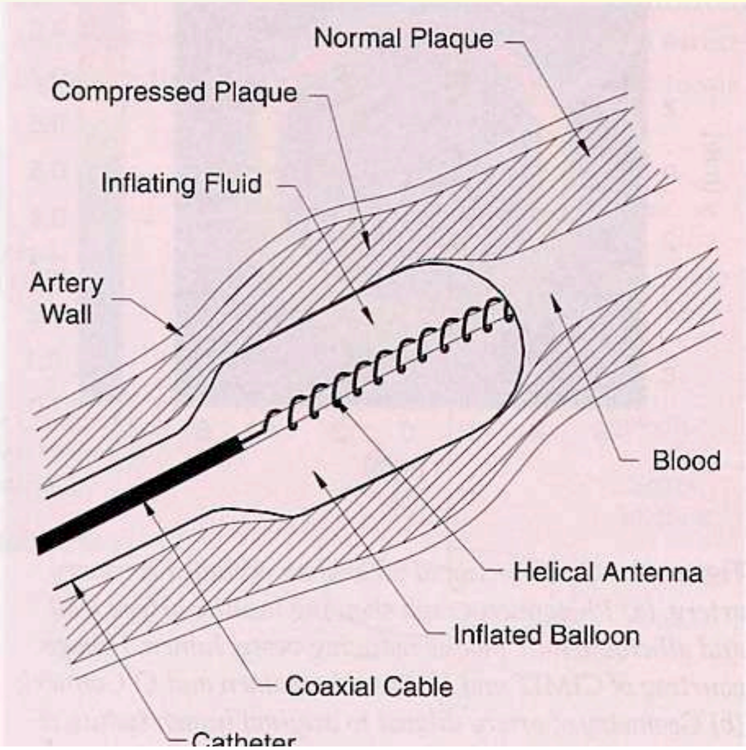


Dual-mode applicator:
spiral & annular slot;
Patch serves as feed

Power deposited 1 cm deep:
Top - annular ring
Bottom - spiral

S. Jacobsen et al, IEEE Trans. BME, 47:1500-08, 2000.

Balloon angioplasty



Helix diameter 3mm, balloon 3mm, artery 4mm, offset 0.5mm

Commercial balloon catheters
2 - 6 mm radius,
0.2 - 18 GHz

C. Rappaport, IEEE Microwave Magazine, March 2002

Cardiac ablation

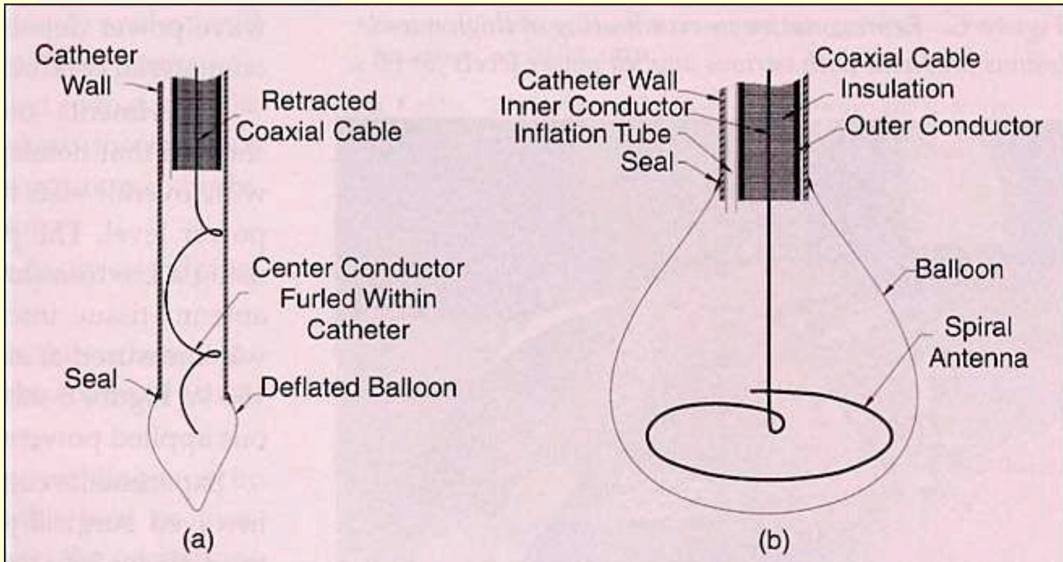


Figure 5. *Schematic view of a wide aperture microwave ablation catheter: (a) stowed position within catheter sheath for insertion/withdrawal and (b) unfurled, radiating position inside inflated balloon.*

C. Rappaport IEEE microwave mag

Treatment of cardiac arrhythmia.

Superior control of the heating region and its depth compared with RF (0.1 - 10 MHz).

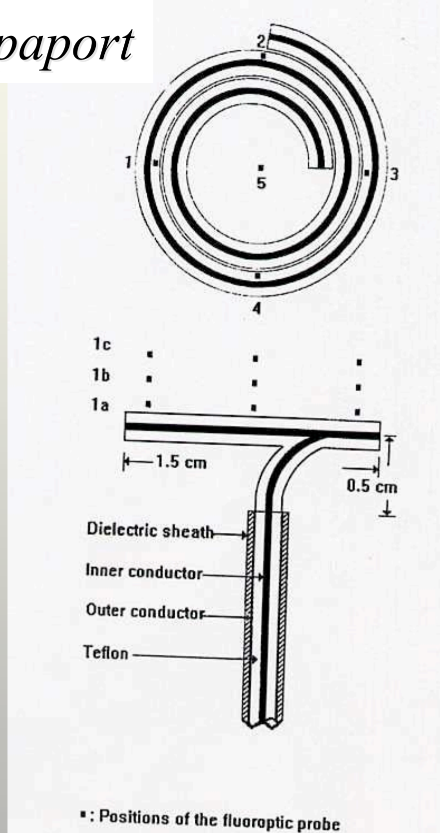
Applicator types:

monopole, dipole with cap, helical coil or spiral antennas; f = 915 MHz or 2.45 GHz, typical

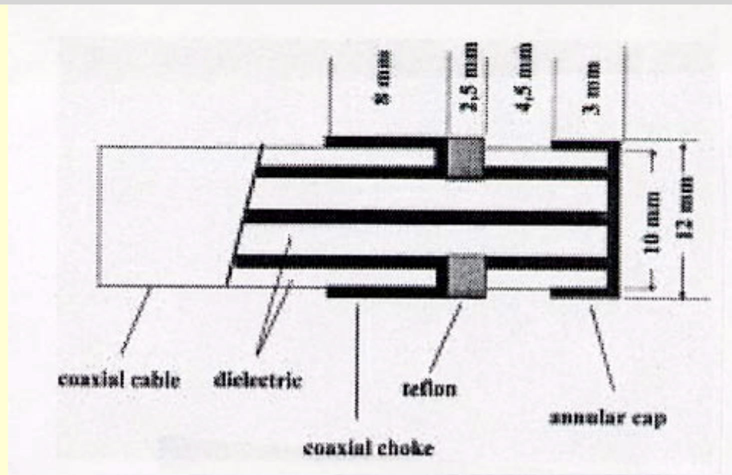
Cardiac ablation

Variety of designs, numerical modeling - “cut & try” design

C. Rappaport

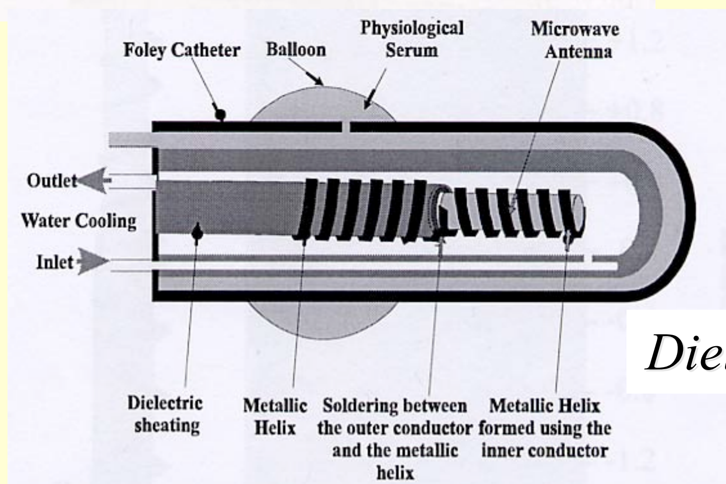


Spiral antenna
5 cm diameter



Cap-choke antenna 915 MHz

Pisa et al, Rome University



Dietch et al, U. Lille

Conclusions

- **Diagnostic applications**: promising results for breast cancer detection
- **Therapeutic applications**: significant progress in many applications; clinical and commercial systems
  - Progress in numerical modeling
  - New designs
  - Heating optimization, monitoring and control
  - Application of computers for numerous tasks
  - Integrated hyperthermia & 3T MRI

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