Clinical Microwave Breast Imaging

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Outline

Motivation – Dielectric Properties – Historical Perspective

Imaging Development & Strategies

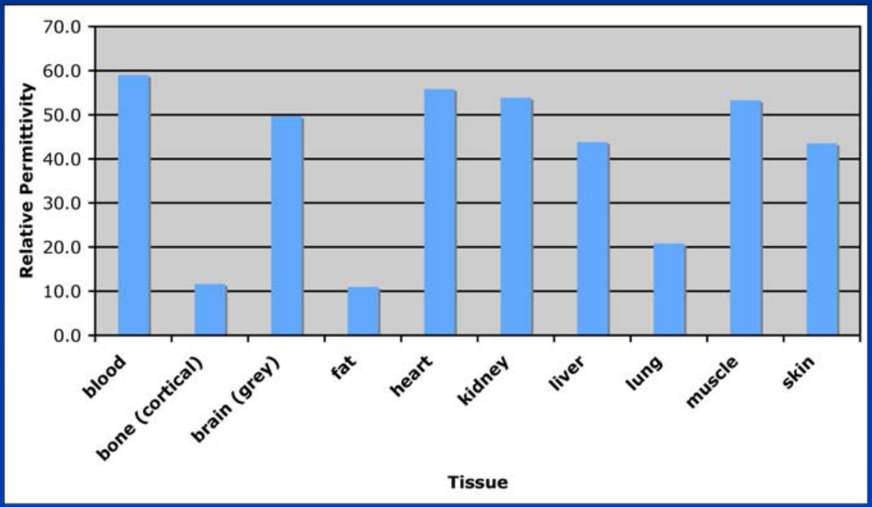
Clinical Results – Diagnosis

Clinical Results – Therapy Monitoring

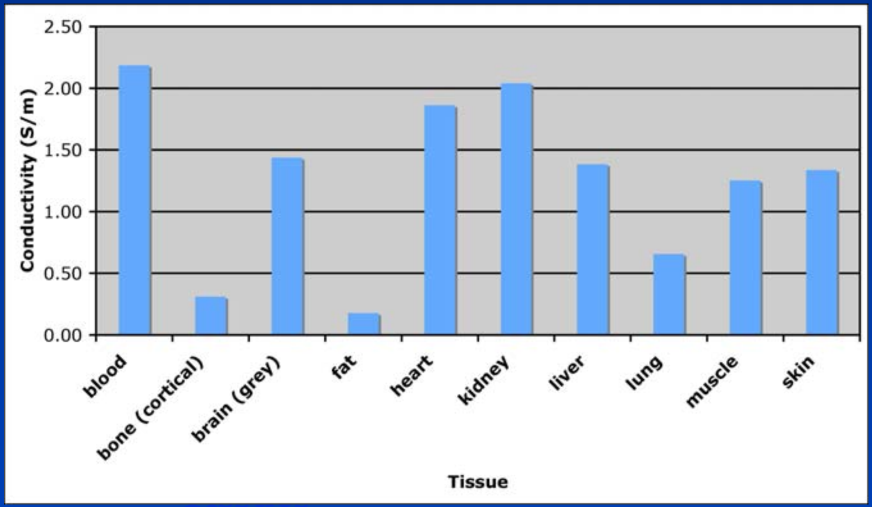
Future Directions – Integration with MR

Tissue Dielectric Properties

Permittivity



Conductivity



[Gabriel et al., *Phys. Med. Biol.* ,vol. 41, pp. 2271-2293, 1996.]

Dielectric Properties Tell Unique Story About Different Tissue

Evolution of Microwave Breast Imaging Concept within the Microwave Community

Earliest Notion –

High Contrast Between Breast & Tumor Tissue Properties

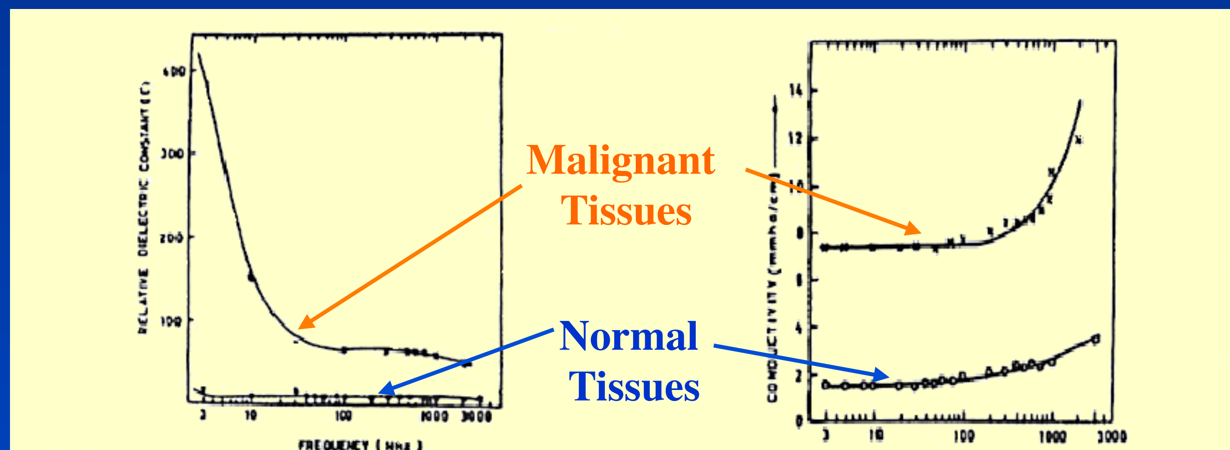


Fig. 5—The relative dielectric constants of normal and malignant human breast tissues [O—O normal tissues; (X—X), malignant tissues]

Fig. 6—The conductivities of normal and malignant human breast tissues [(O—O), normal tissues; (X—X), malignant tissue]

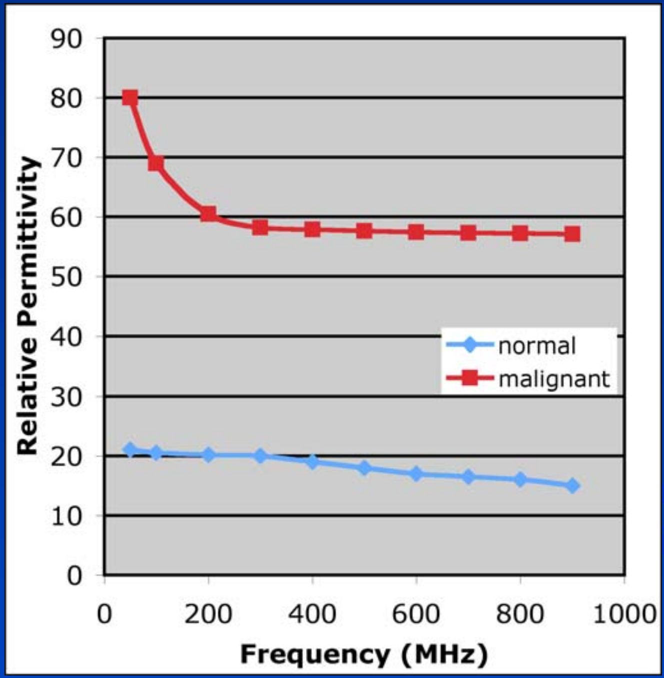
[Chaudhary et al., *Ind. J. Biochem. & Biophys.*,vol. 16, pp. 76-79, 1984.]

Implications – Easy Imaging Problem – High Contrast

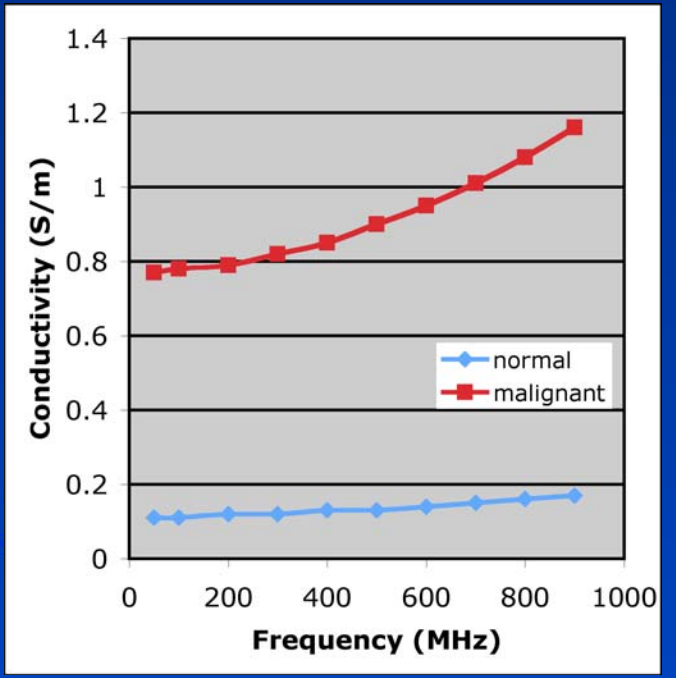
Later Interpretation

Still High Contrast Between Breast & Tumor Tissue Properties

Permittivity



Conductivity



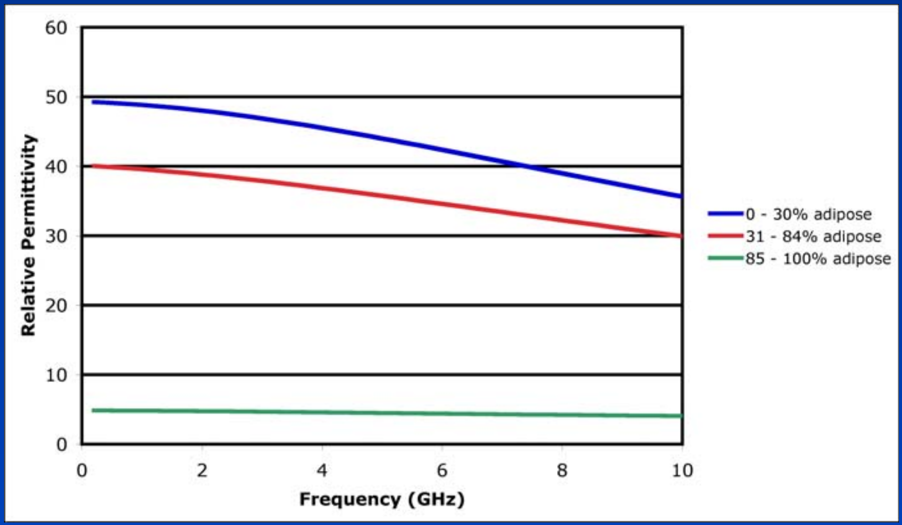
[Joines et al., *Medical Physics*, vol. 21, pp. 547-550, 1994.]

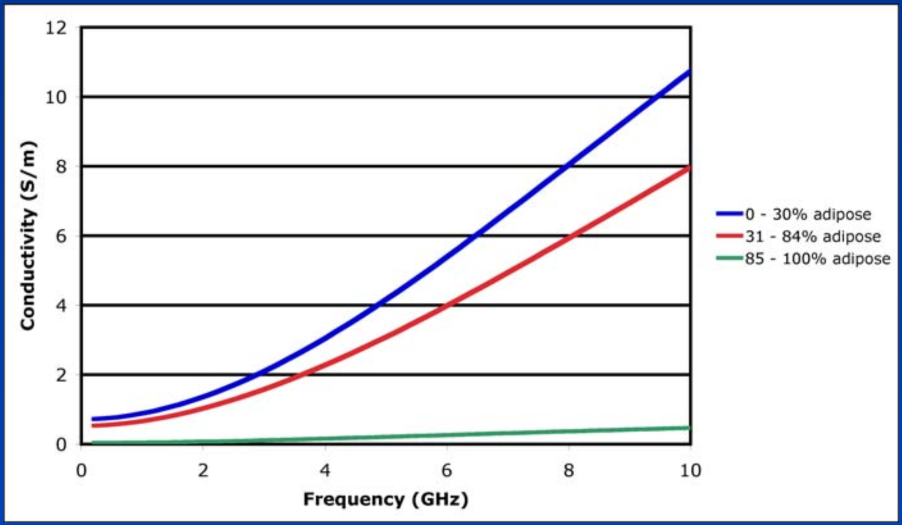
Implications – Easy Imaging Problem – High Contrast

Early Contradictions – Much Higher Normal Permittivity

More Refined Understanding

Lazebnik et al 2007





Broad Range of Fibroglandular Dielectric Tissue Properties

Dependent on Percentage of Interposed Adipose Tissue

Lazebnik et al, *Phys. Med. Biol.*, vol. 52, pp. 2637-2656, 2007.

Broader Survey of Medical Literature

Woodard and White (1986) –

Measured Water Content of Different Tissues in the Context of Radiographic Dosimetry

	Water Content (%)	
Adipose Tissue -	11.4 – 30.5	
Mammary Gland -	30.2 – 72.6	(Wide Range)

Microwave Properties are Driven by Water Content

Woodard HQ & White DR, "The Composition of Body Tissues," *Brit. J. Radiol.*, vol. 59, pp. 1209-19, 1986.

Nearly Forgotten Early Tissue Dielectric Property Studies

Example:

Schwan & Foster

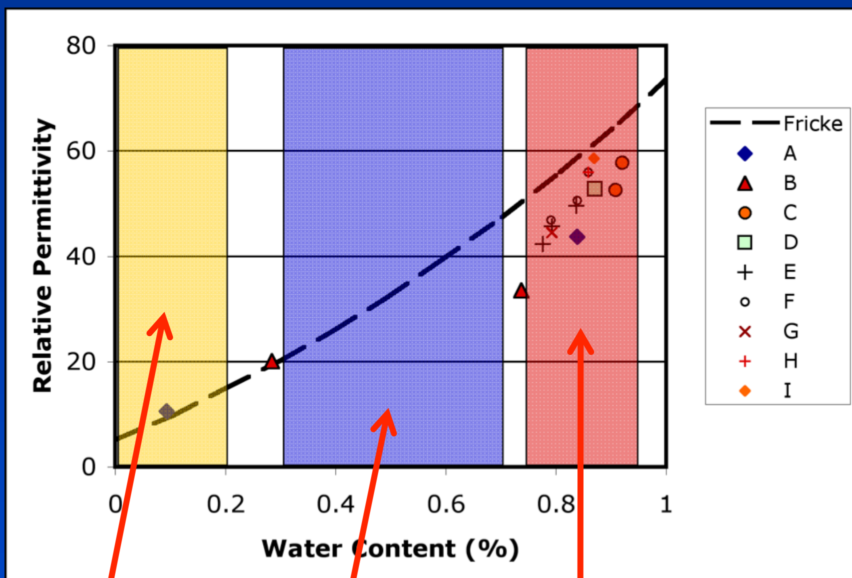
Measurement Techniques Somewhat Primitive Compared with Current Technology

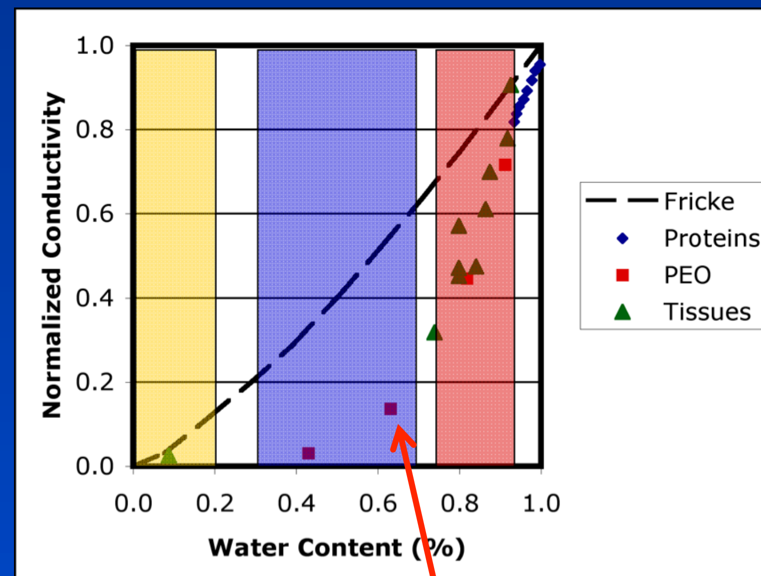
However, Early Theory & Models are Still Relevant

Maxwell-Fricke Dielectric Property Mixture Laws

Foster & Schepps (1981) –

Properties Vary Monotonically with Water Content





Fat

Fibroglandular

Tumor

$$\frac{\varepsilon - \varepsilon_w}{\varepsilon + x\varepsilon_w} = p\,\frac{\varepsilon_p - \varepsilon_w}{\varepsilon_p + x\varepsilon_w}$$

Bound Water Effects

Foster KR & Schepps JL, *J. Microwave Power.*, vol. 16, pp. 107-119, 1981.

Outline

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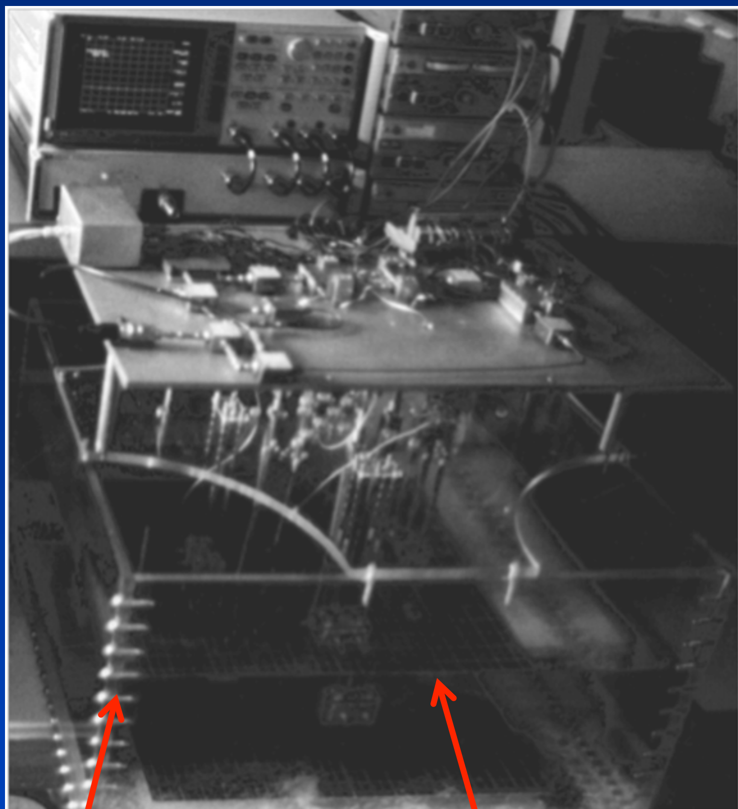
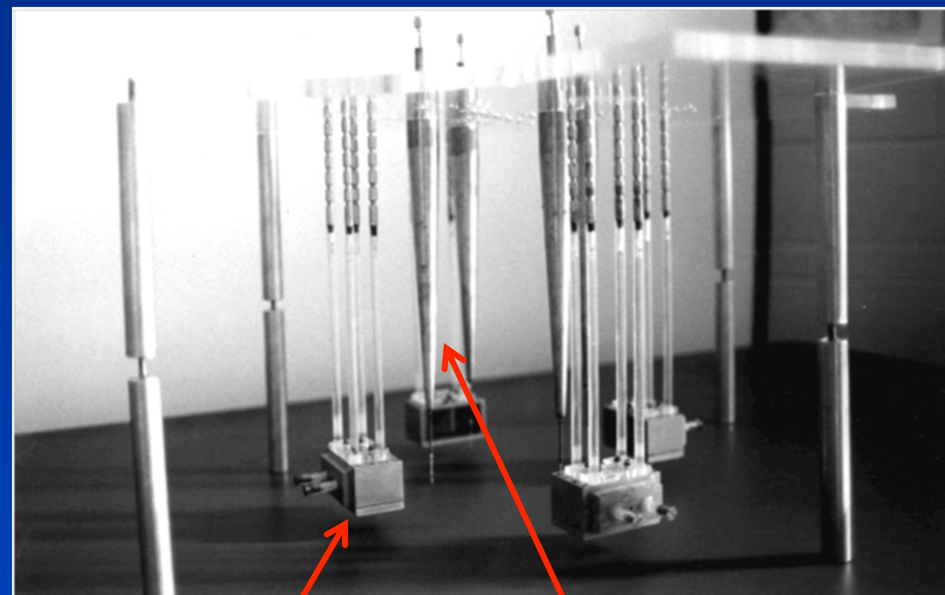
Clinical Results – Diagnosis

Clinical Results – Therapy Monitoring

Future Directions – Integration with MR

Earliest System 1993-95





Very Large Tank

Lossy Liquid - Saline

Water-Filled Waveguide Antennas

Monopole Antennas

Bench Top System – Circa 1995-97

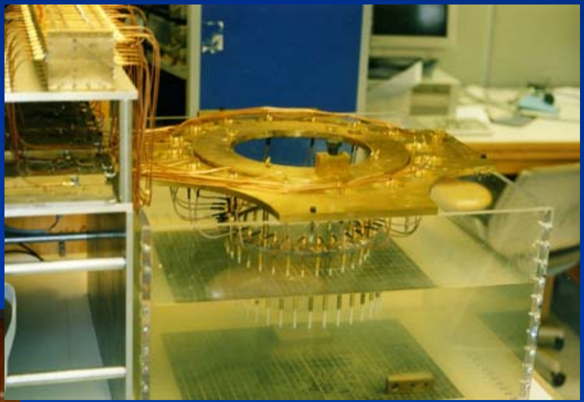
Important Innovations:

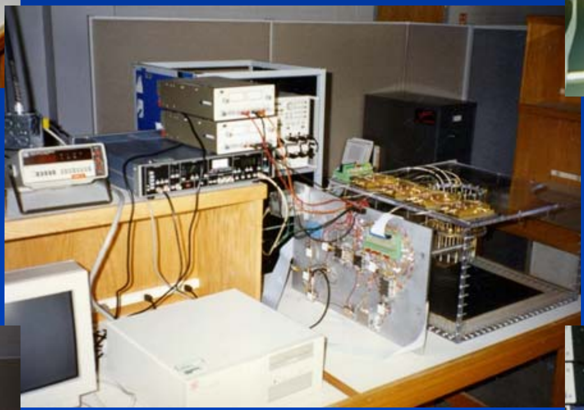
1) Lossy Liquid -
   - a) Suppressed Evanescent Waves
   - b) Broadened Antenna Bandwidth

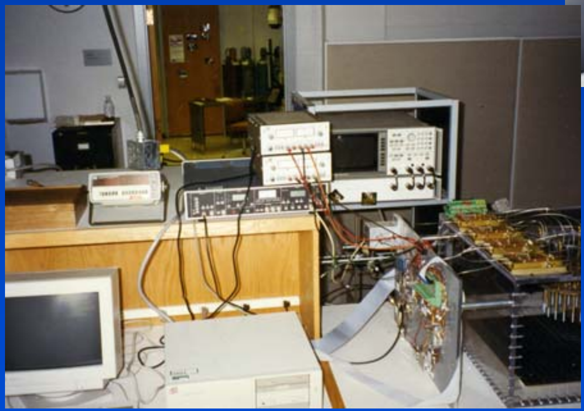
2) Monopole Antennas –
   - a) Could Be Packed Close to Target – Less Loss
   - b) Most Easily Modeled – Very Accurate

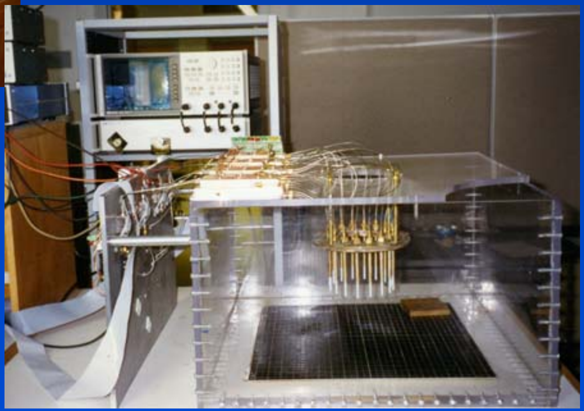
3) Custom Acquisition Hardware Development
   Strategies to Restrict Signal Leakage –
   < -140 dB

Bench Top System – Circa 1995-97

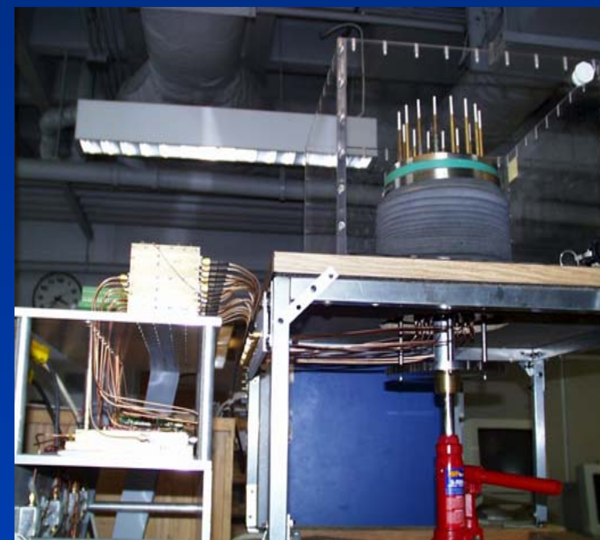




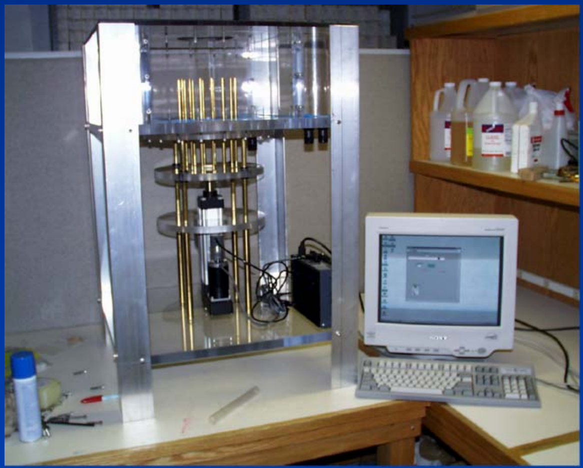


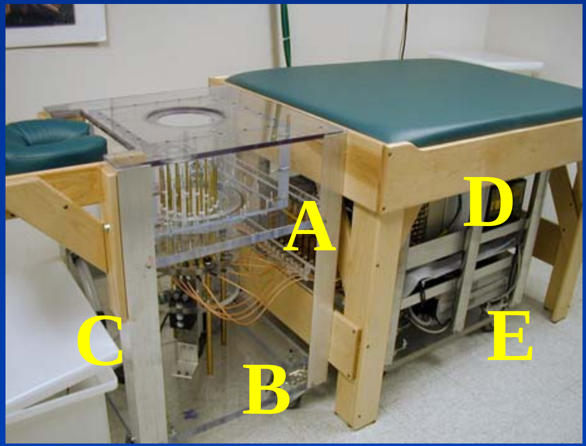


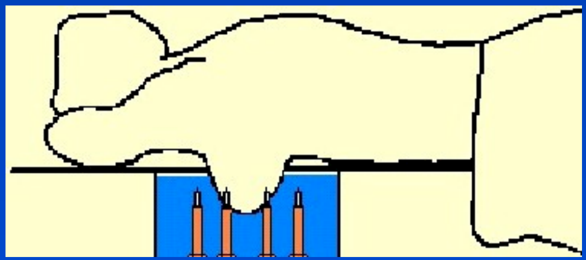
First Clinical System – Circa 1998-2002



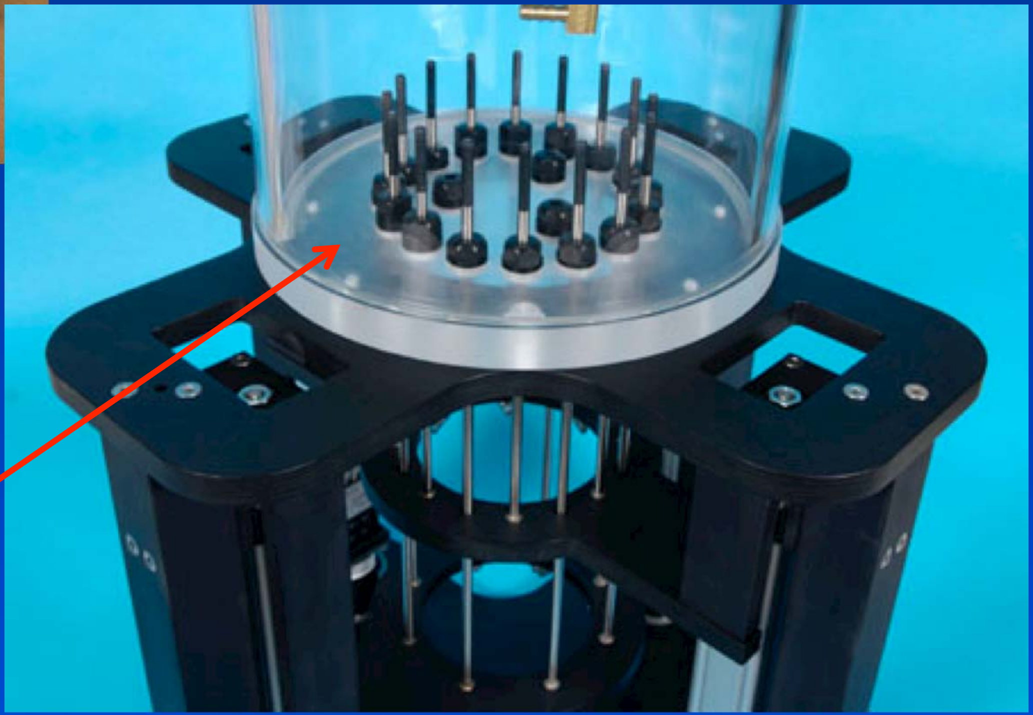
Second Clinical System – Circa 2003-2008







Current System



Clinical Interface

Illumination Tank

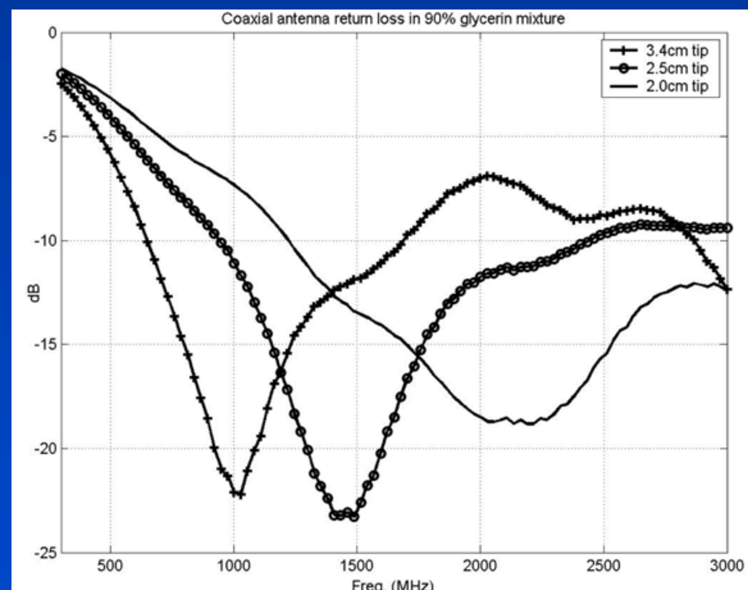
Monopole Antenna – Much Maligned

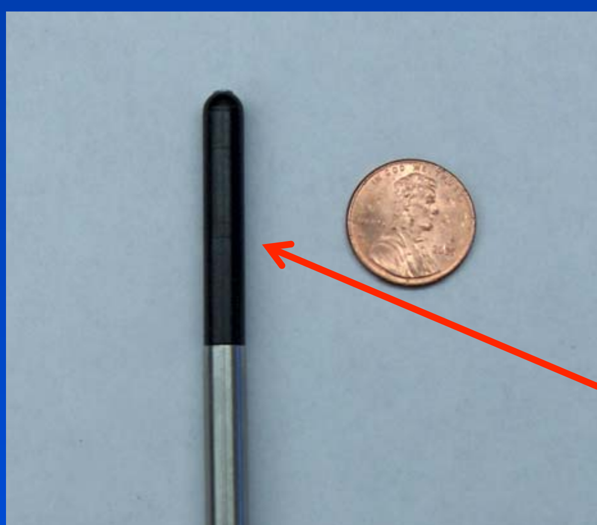
- Point Source in 2D – Line Source in 3D
  - Pack Antennas Close to Target- Min. Transmit Distance
    - Resolution Improves with Reduced Antenna to Target Distance
  - More Accurate 2D Representation
    - e.g. Model-Based Approach
- Wide Bandwidth
  - Log Transform Algorithm Not Possible in Some Situations Without It
- Inexpensive
  - Easily Integrated into 3D Illumination Configuration

Monopole Antenna

Simple Design

Standard Semi-rigid coax supported in stainless steel casing

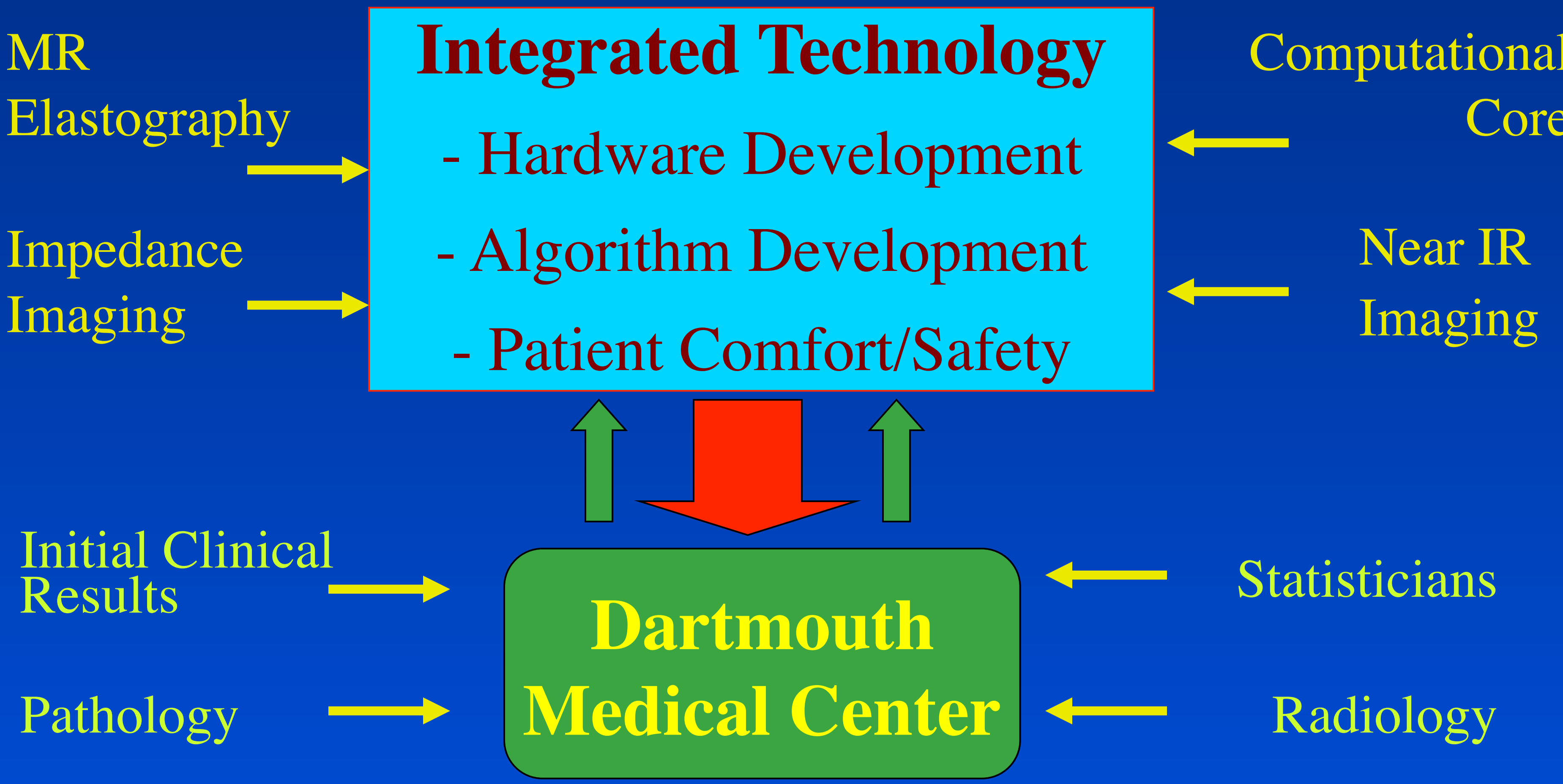




Radome

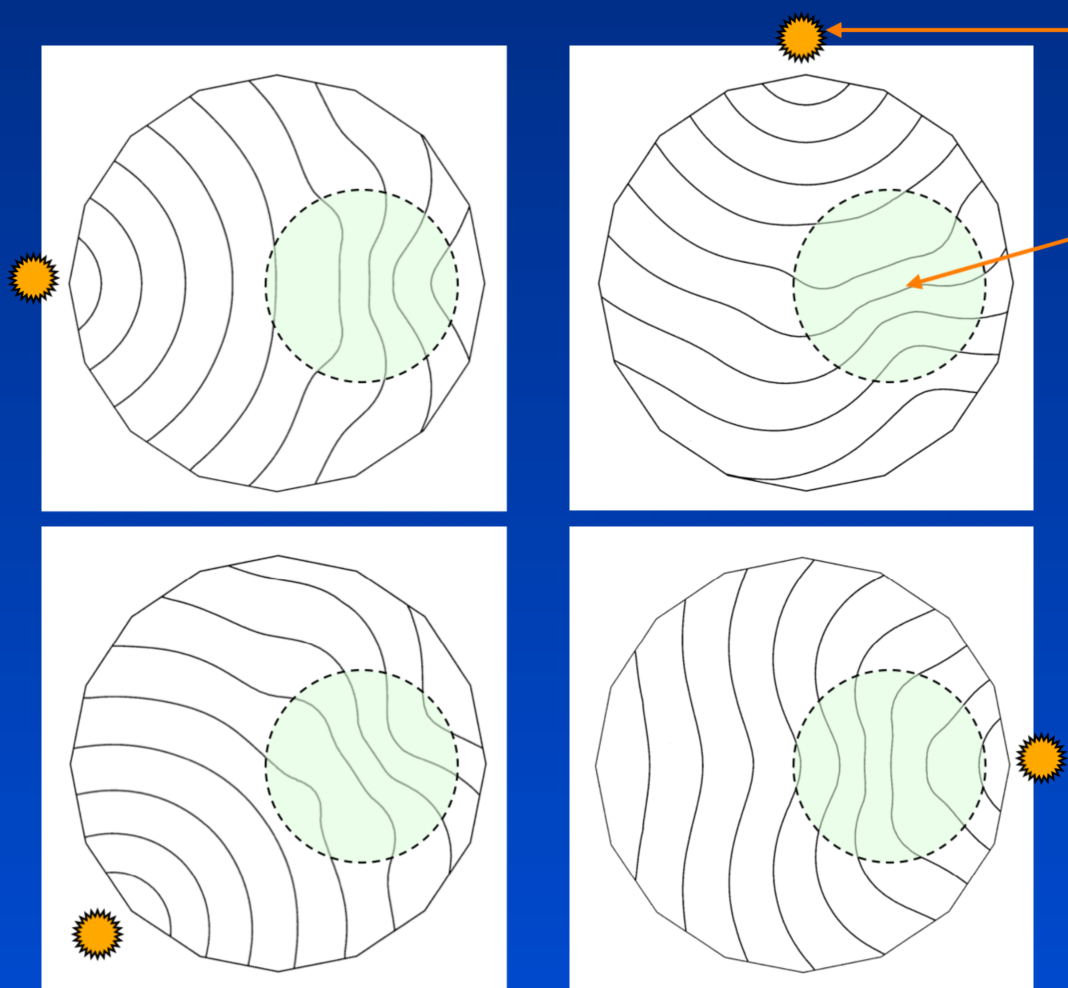
Alternative Breast Imaging Program Project

Microwave Imaging Development



> 500 Patients Imaged

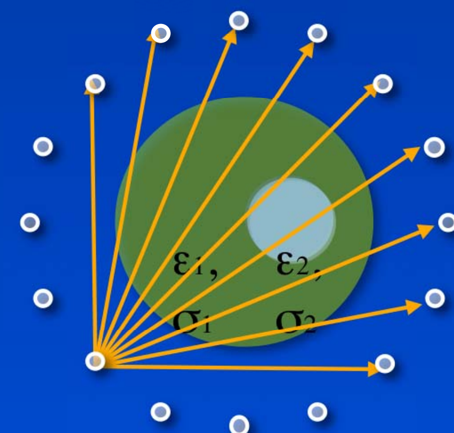
Forward Solution



Monopole Source

Scattering Object

Antenna Array & Imaging Configuration



Gauss-Newton Iterative Algorithm

$$\min \quad \left\| E^{m} - E^{c}\left(k^{2}\right) \right\|^{2}$$

Nothing Fancy

Ideal For Nonlinear Parameter Estimation Problems

Extensive Literature in the Probability & Statistics Domain

Forward Solution

Requires an Accurate Forward Solver

- Finite Element (FE)
- Finite Difference Time Domain (FDTD)
- Method of Moments (MOM)
- Integral Equations

All Have Merits – Efficiency is a Factor – Computations Can be Long

Log Transformation

Adopted from NIR Area – Ideally Suited For Cases Where Power Levels Differ Over Many Orders of Magnitude

$$\min \quad \left\| \Gamma^{m} - \Gamma^{c}\left(k^{2}\right) \right\|^{2} + \left\| \Phi^{m} - \Phi^{c}\left(k^{2}\right) \right\|^{2}$$

Log Magnitude

Phase

- Emphasizes Greatest Relative Amplitude and Phase Projections
- Does Have to Deal with the Phase at Microwave Frequencies

Regularization

Inverse Problem is Generally Ill-Posed and Ill-Conditioned –
Requires Some Regularization

$$\min \left\| \left\|\Gamma^m - \Gamma^c\left(k^2\right)\right\|^2 + \left\|\Phi^m - \Phi^c\left(k^2\right)\right\| \right\|^2 + L\left\|k^2 - k_o^2\right\|^2$$

Regularization Term

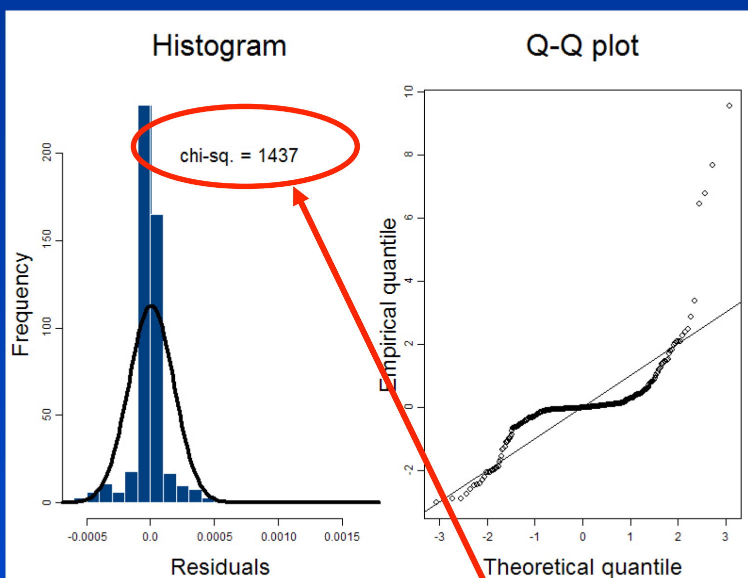
The Log Transform is Not a Regularization –

- Has Rigorously Developed Mathematical Provenance
- Operates on The Kernal of Equation
- Linearizes The Process at Each Iteration
- Improved Convergence Behavior – Against Statistical Criteria

Variance Stabilizing Transformation

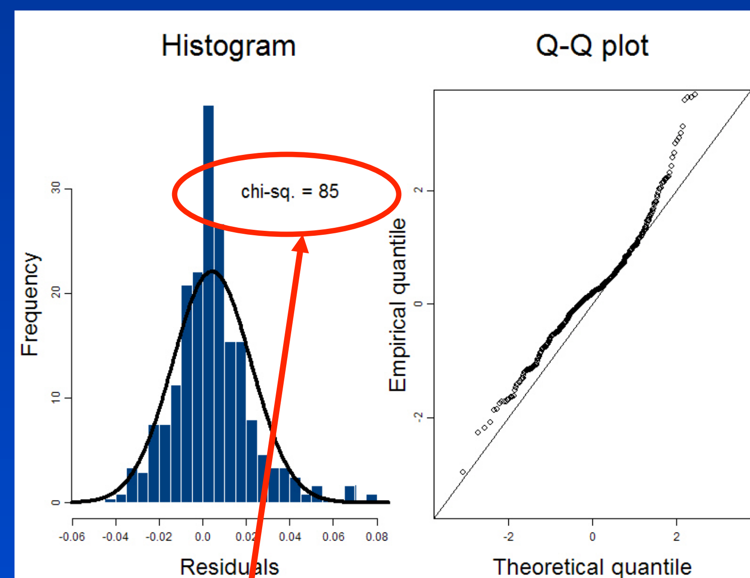
Residual Error Analysis

Standard Least Squares



Not Normal

w/ Log Transformation



Normal

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Diagnosis Studies

Goals

1) No one Has Ever Seen A Microwave Image of a Tumor – We Wanted Experience With Tumor Cases

2) Experience with Baseline Normal Cases

3) Optimization of Coupling Bath
   - Matching Permittivity
   - Used Our Own In Vivo Data for Study

4) 2D and 3D Data

5) Clinical Summary

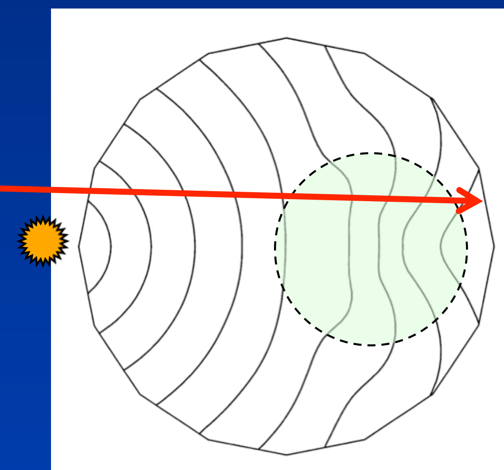
In Vivo Bath Determination

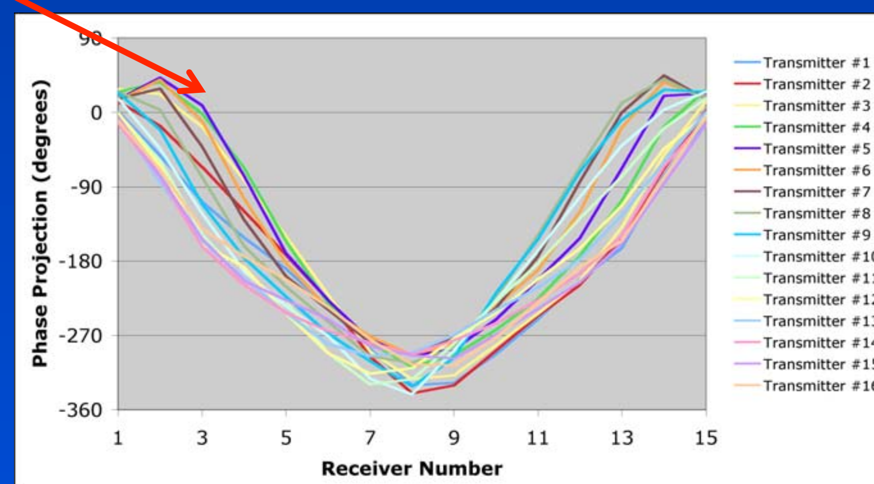
Phase Projection Gives General Info On Size and Contrast of Object

Independent of Biases From Reconstruction Process

Not Dependent on Ex Vivo Tissue Studies

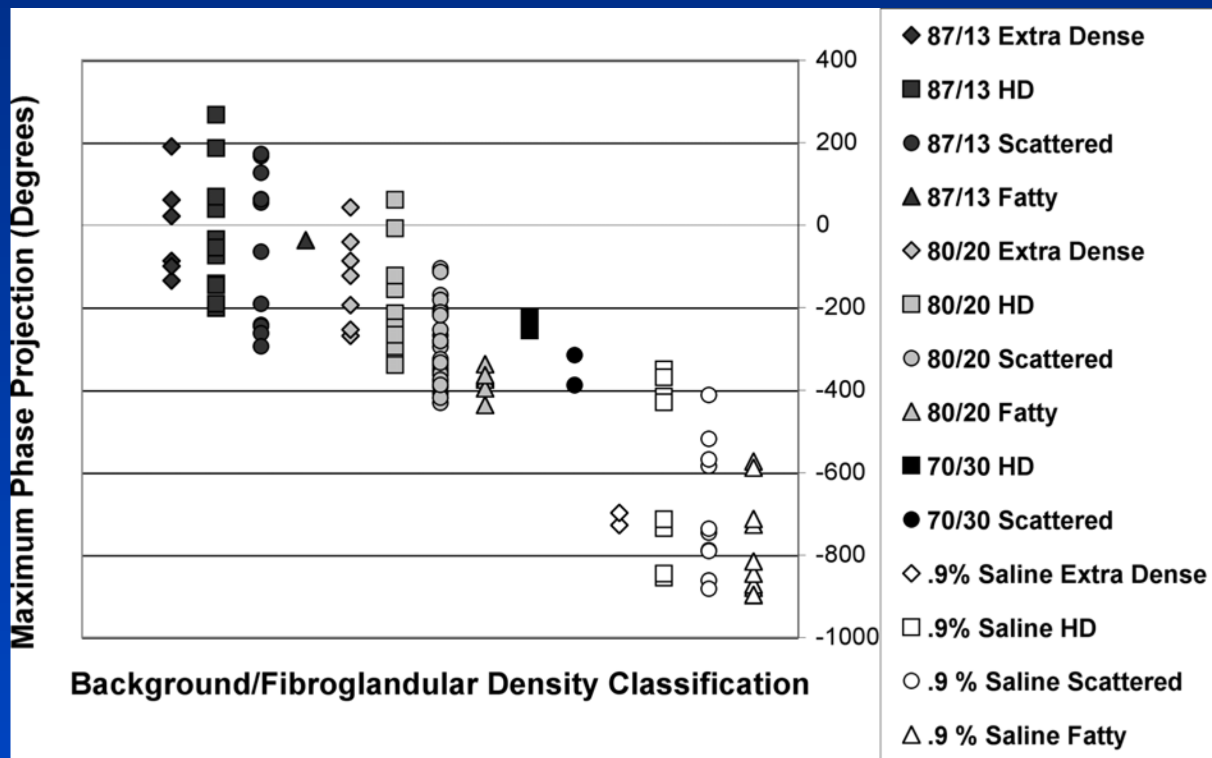
Maximum Independent of Illumination Direction





In Vivo Bath Determination

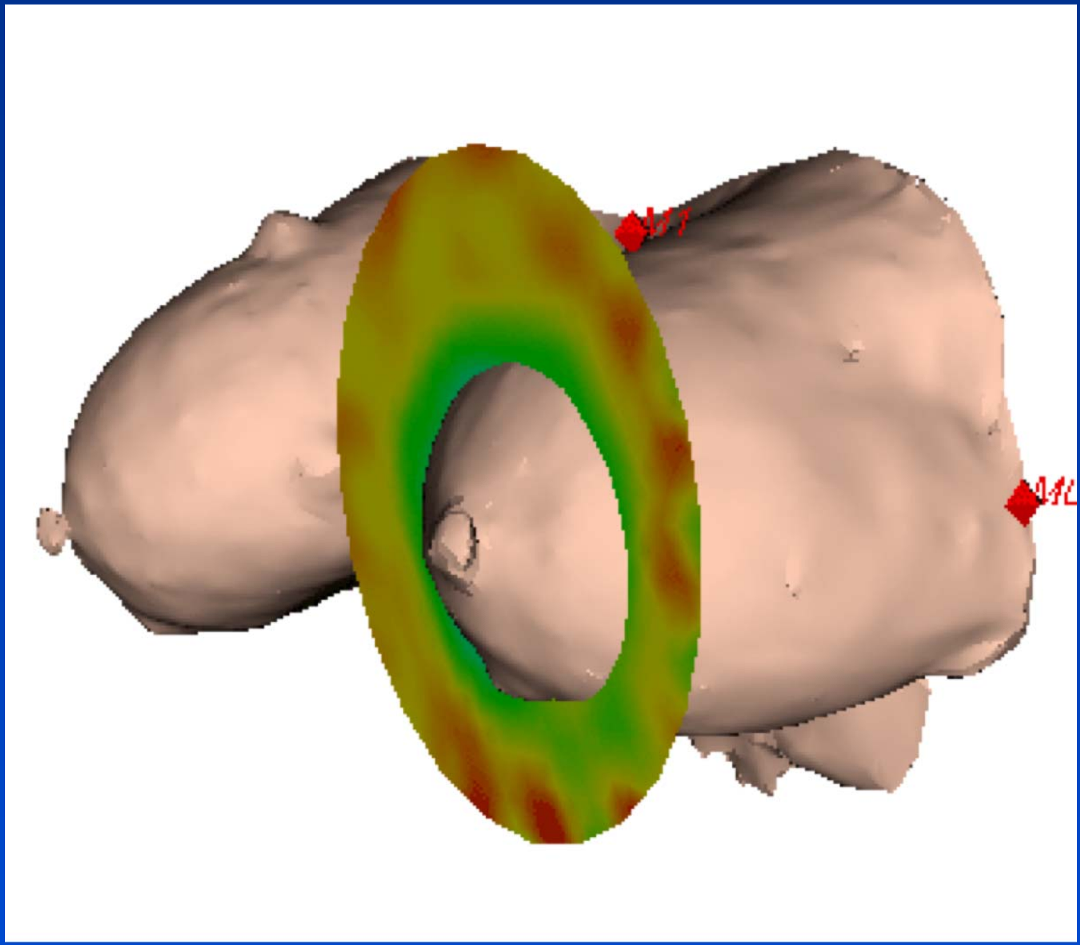
Phase Projections as a Function of Bath Contrast and Breast Density –



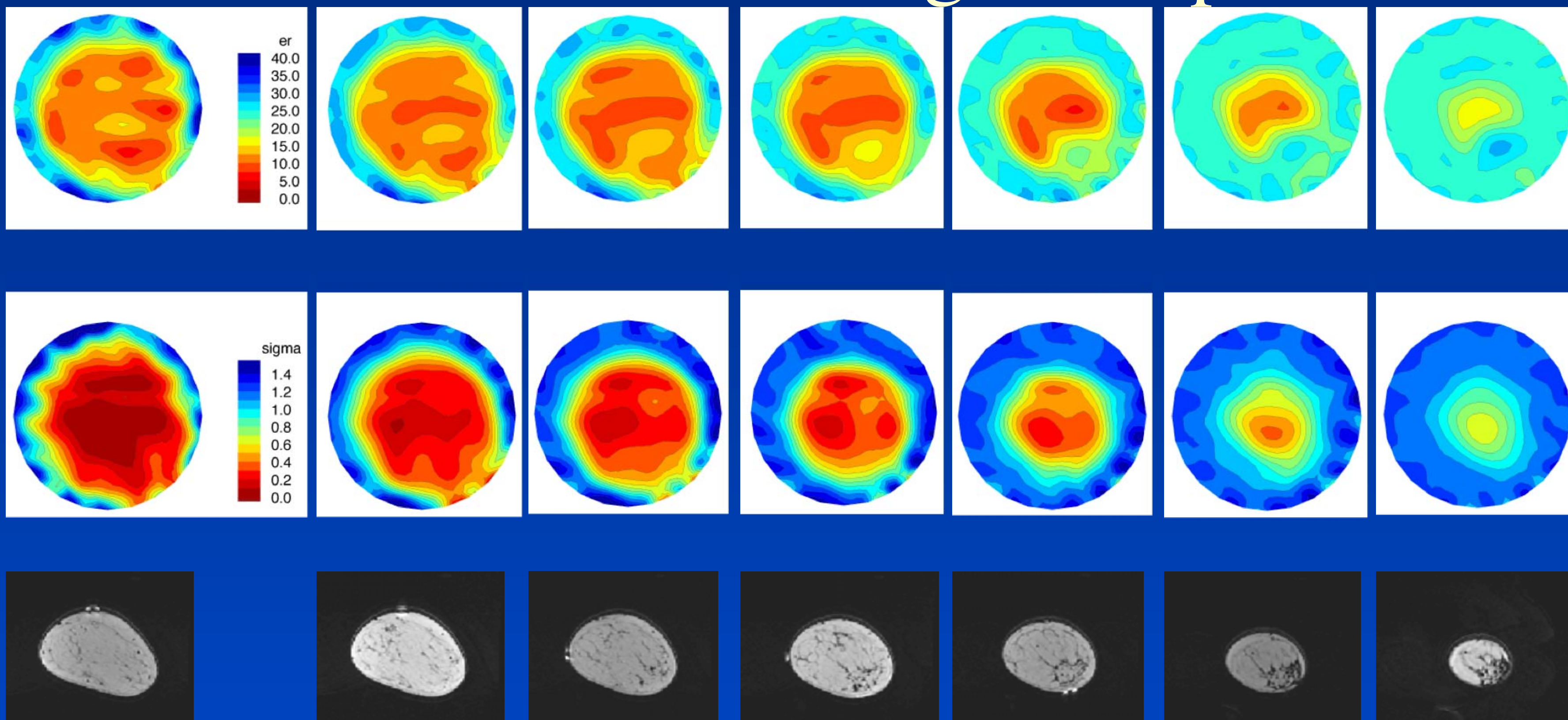
Saline – Highest Contrast

87:13 Glyerin:Water Bath – Lowest Contrast

Coronal Image Slice Orientation



MR - Microwave Image Comparison



P1 P2 P3 P4 P5 P6 P7

Patient S534 - Fatty to Scattered Dense - Left Breast

Normal Breast Microwave Images

Coronal Planes

- Recovered Perimeters Shrink from Chestwall to Apex

Breast Properties Are Generally Quite Low

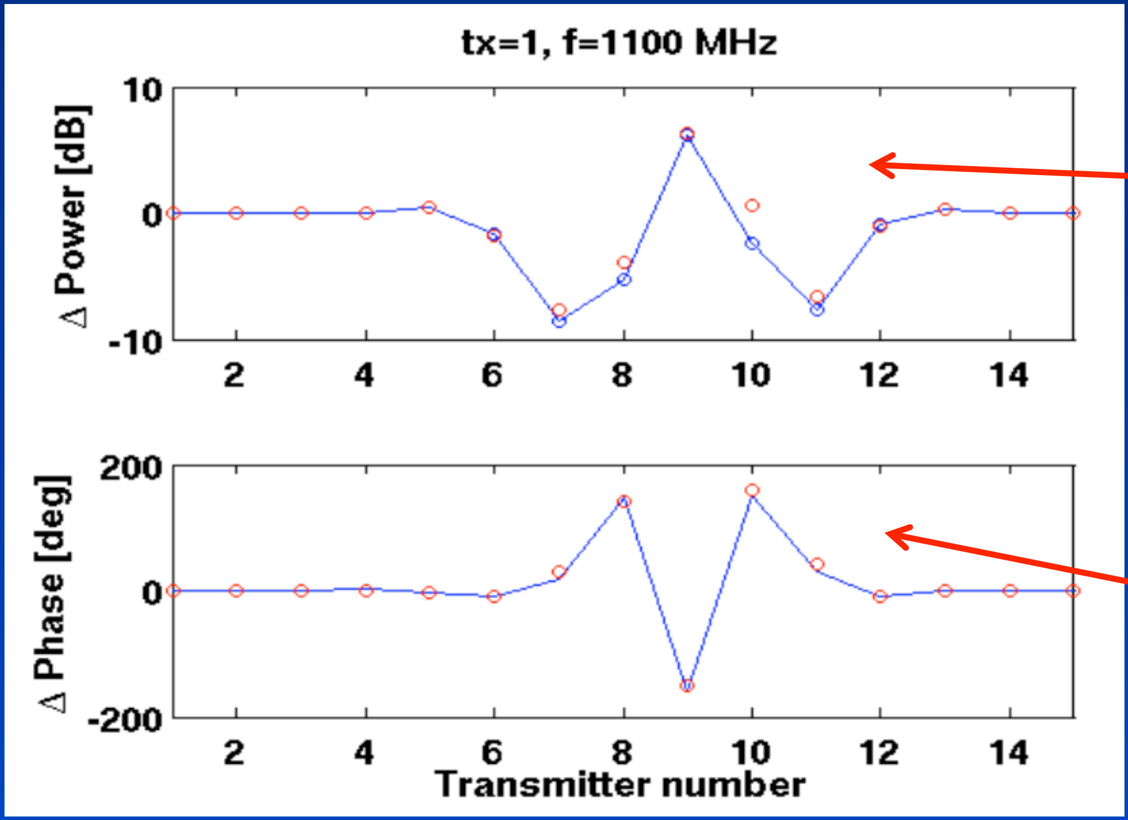
- Permittivity and Conductivity

Gradient Between Background and Breast

Permittivity Tracks Normal Water Content

- Most Prominently Fibroglandular Tissue

2D to 3D Data Comparison



Magnitude

Phase

Red Dots Mimic the Actual 3D Measurements

Blue Lines Mimic the 2D Reconstruction Algorithm

Speculations on Why the 2D Algorithm is So Good

Placement of Antennas Close to the Target

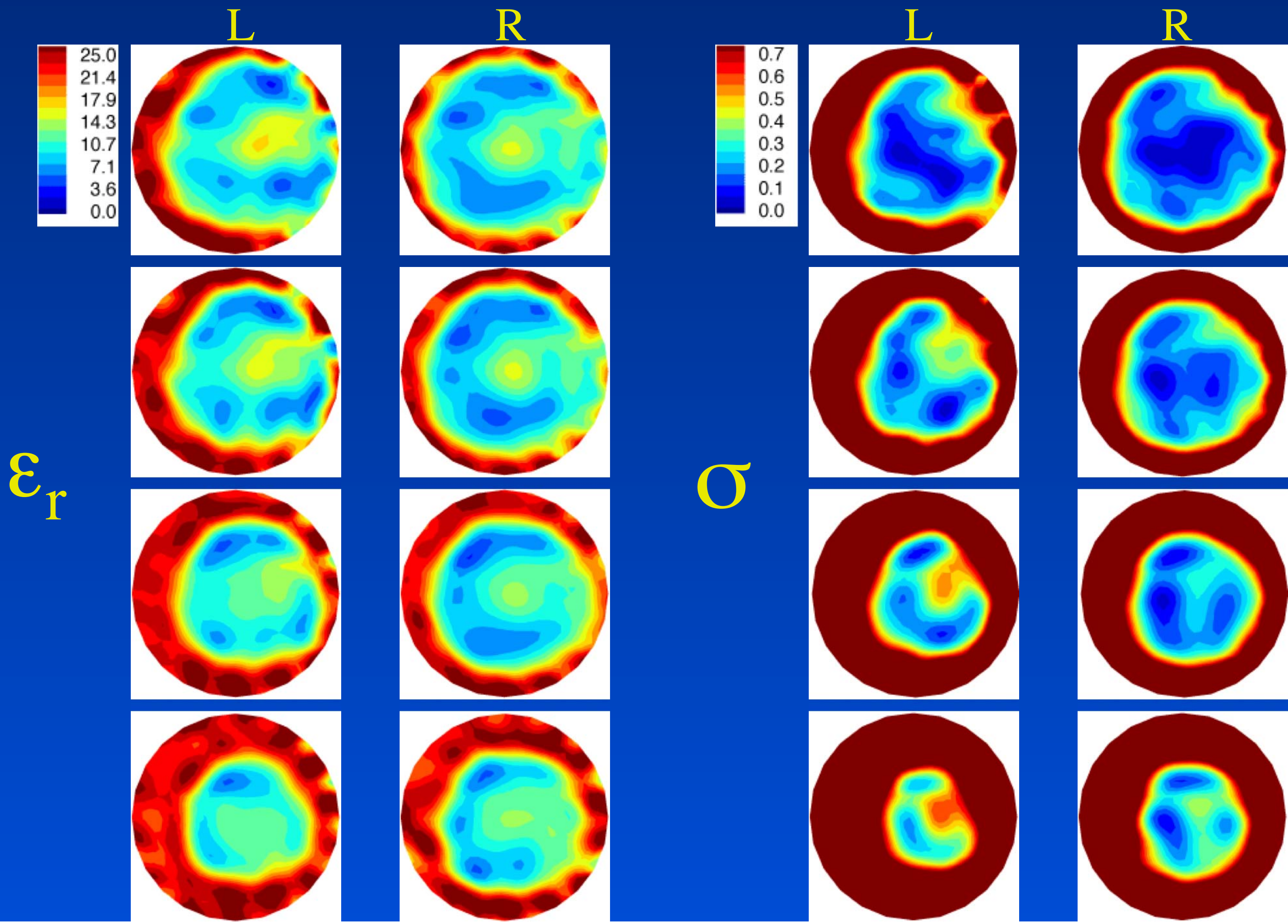
More Closely Emulates Cylindrical Geometry

Lossy Medium

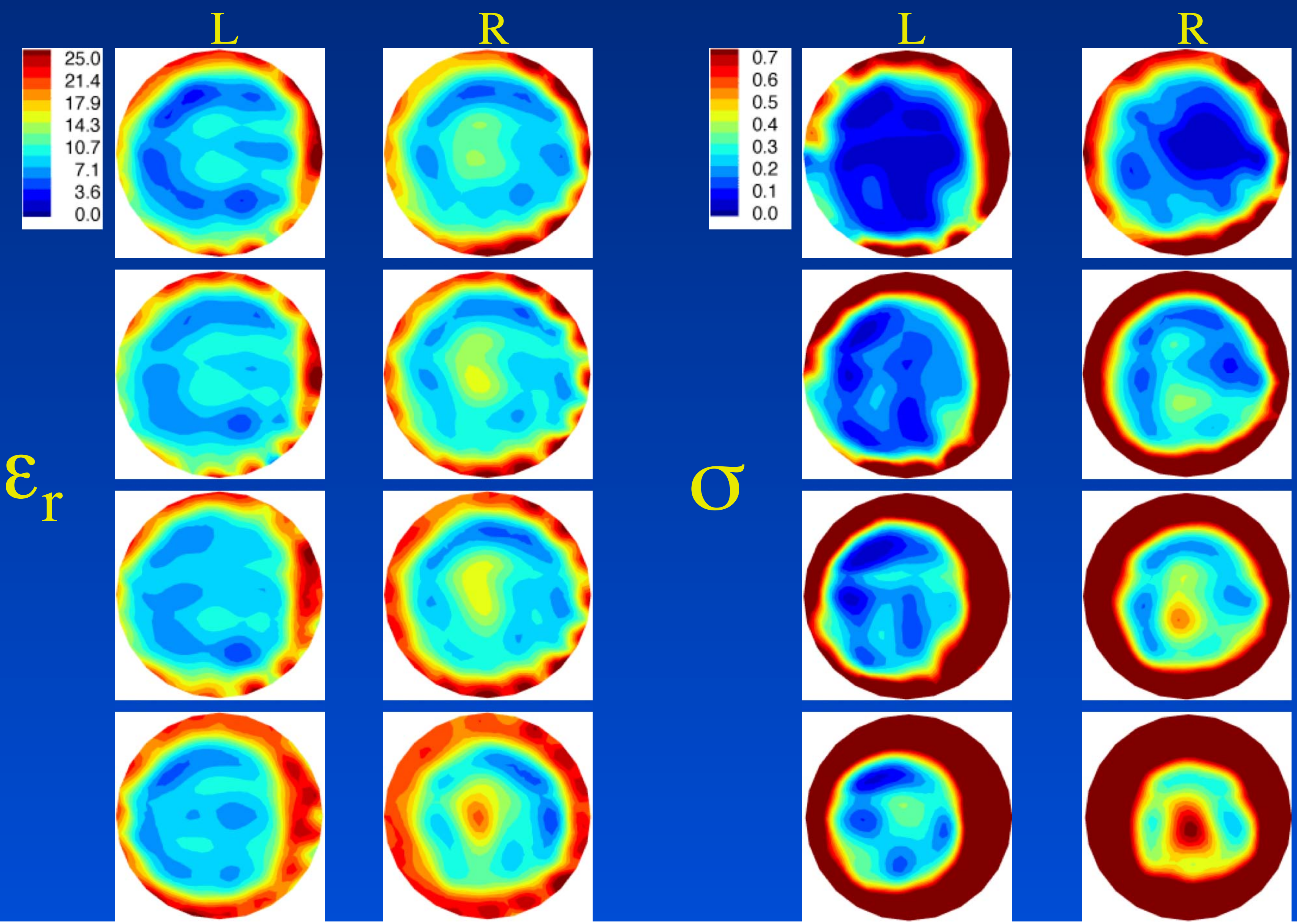
Severely Attenuates Signals Out of Plane

Specific to Our Implementation

Patient 2025

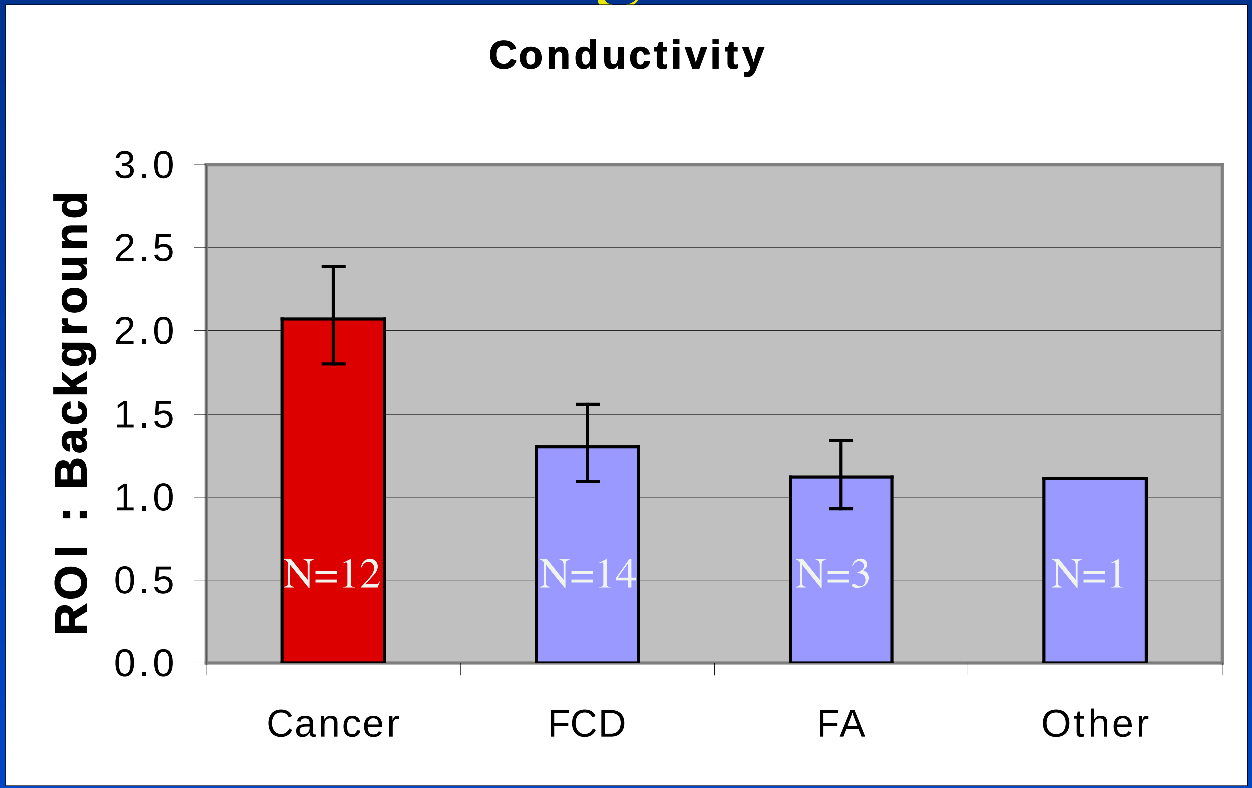


Patient 2094



Clinical Contrast

Cancer vs. Benign Abnormalities



P-value < 0.001

Tumors greater than 1 cm

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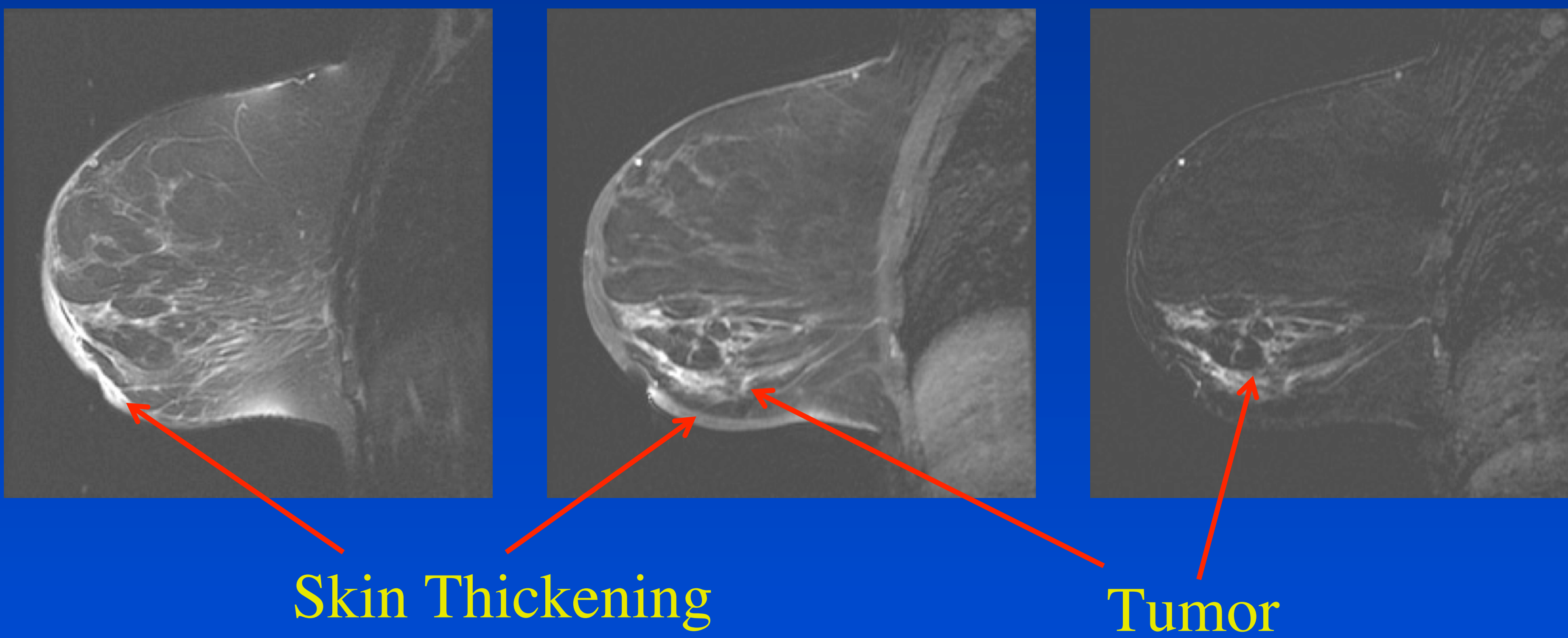
Neoadjuvant Chemo Therapy

- Administered Prior to Surgery
  - Generally Larger Tumors
- Shrink Tumors
  - Allows for Breast Conservation Surgery
- Surrogate Indication for Later Tumor Response After Surgery
  - Minimal Current Prognostic Capability

MR Images of Skin Thickening

Patient 1914 – Heterogeneously Dense Breast – 36 Years Old

T2 | T1 – Gad Enhanced | Subtraction



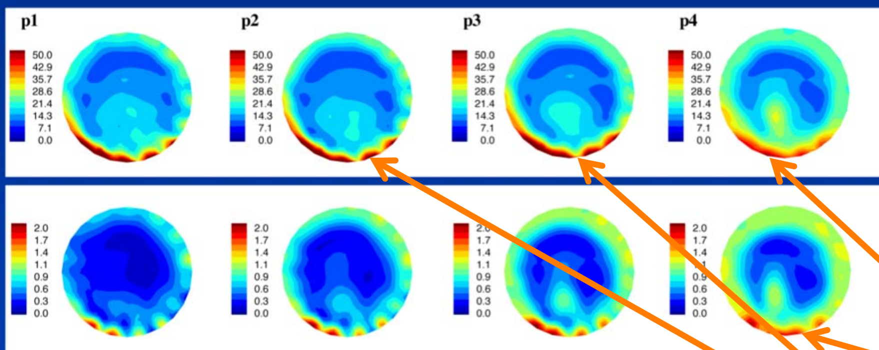
Patient 1914

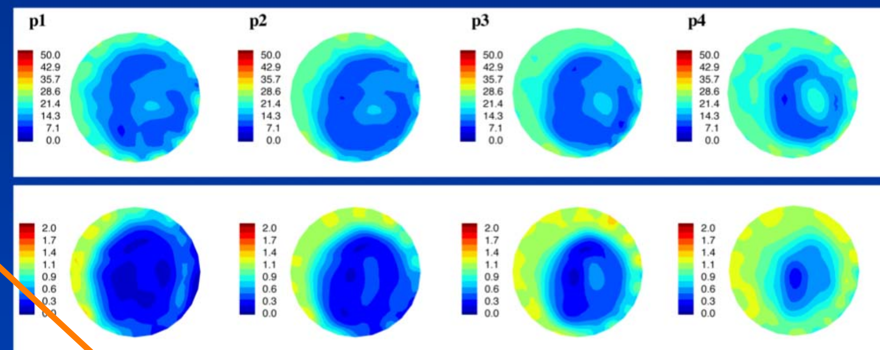
Right Breast - Start Chemo

Left Breast

ε_r

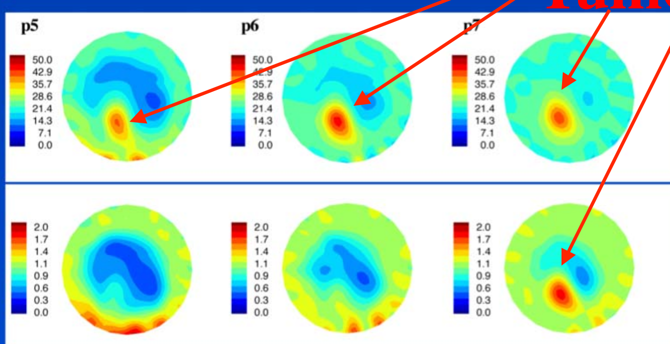
σ

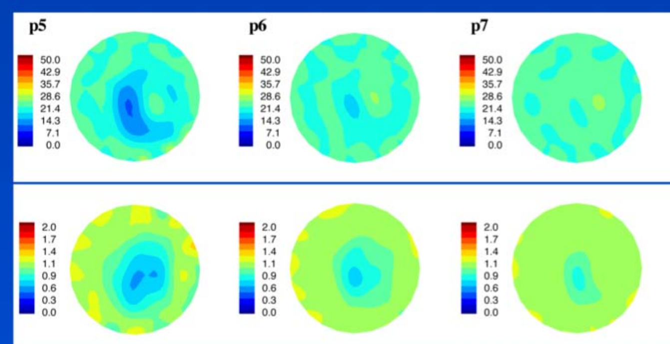




Thickened Skin

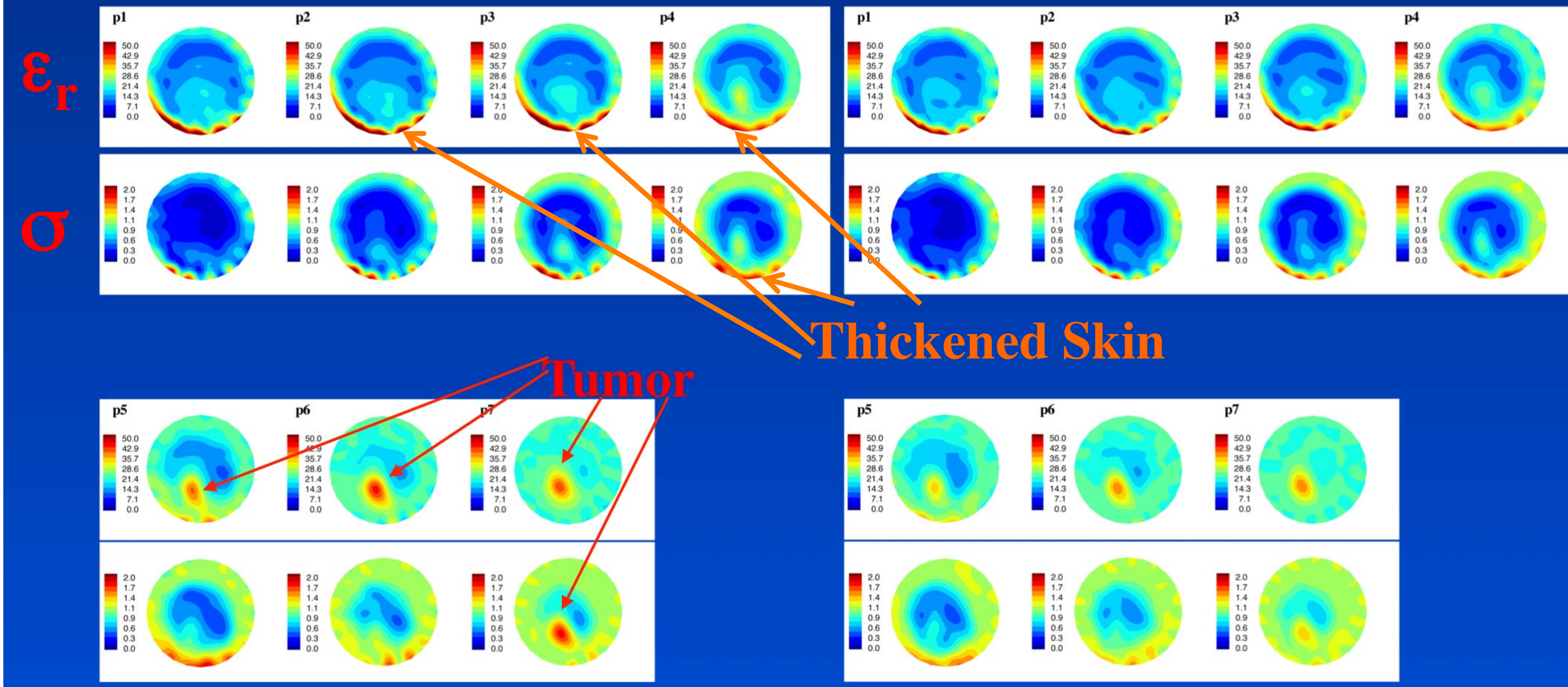
Tumor





Patient 1914

Right Breast - Start Chemo | **Right Breast - After 2nd Cycle**

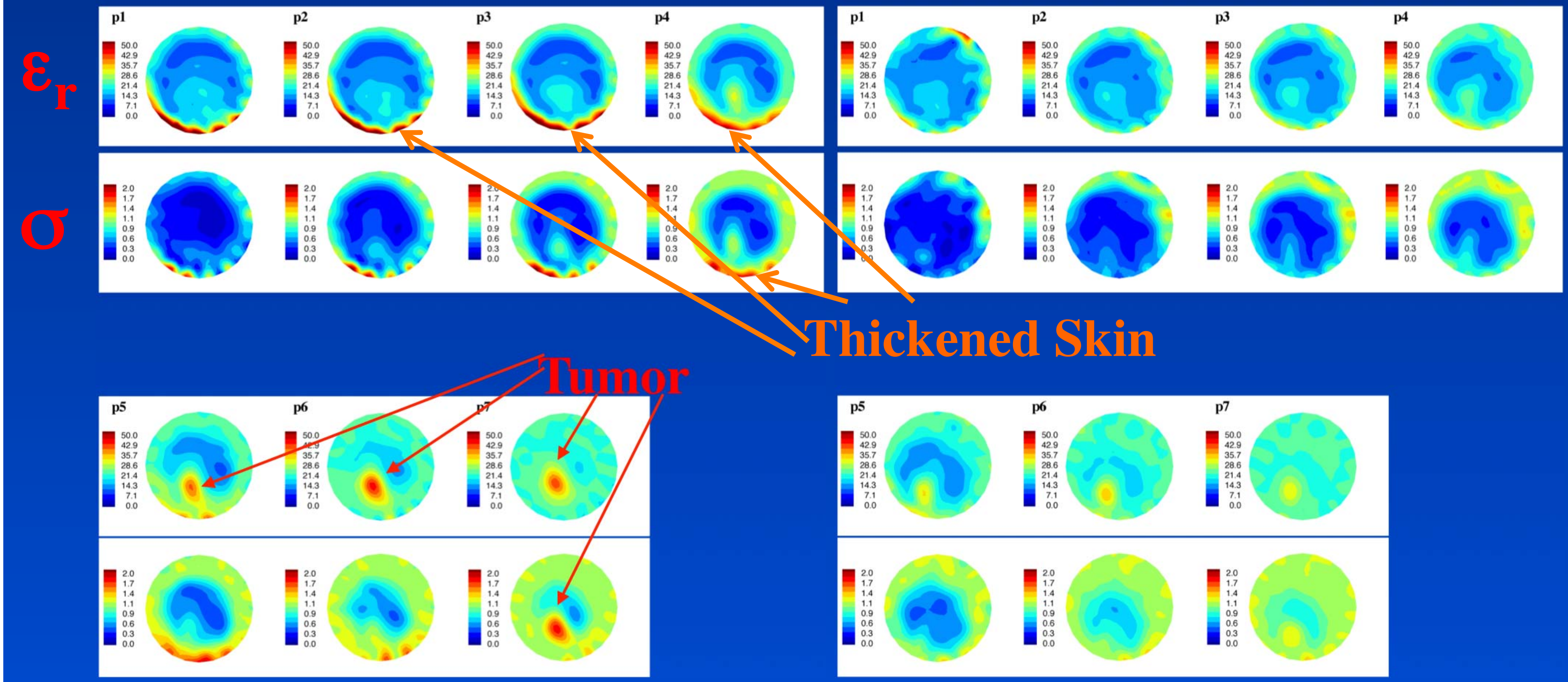


Thayer School of Engineering at Dartmouth College

2010 Advances in Breast Cancer Research
University of Arkansas– October 26-29, 2010

Patient 1914

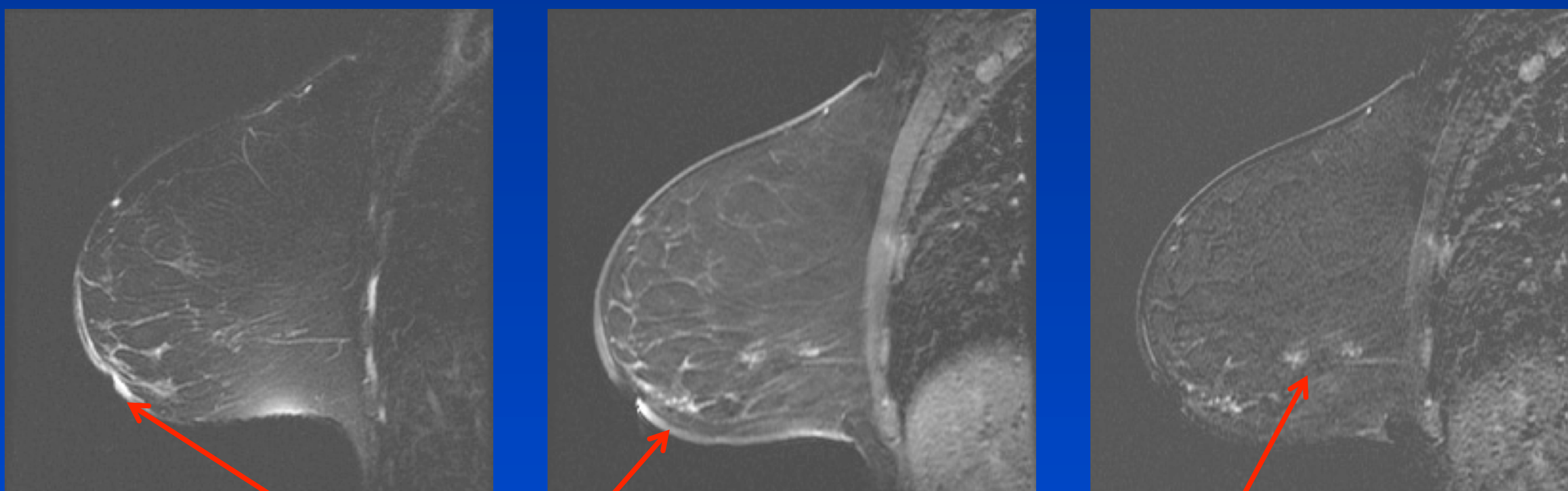
Right Breast - Start Chemo | **Right Breast - After 4th Cycle**



MR Images After Therapy

Patient 1914 – Heterogeneously Dense Breast – 36 Years Old

T2 | T1 – Gad Enhanced | Subtraction



Skin Thickening (Reduced)

Tumor - Treated

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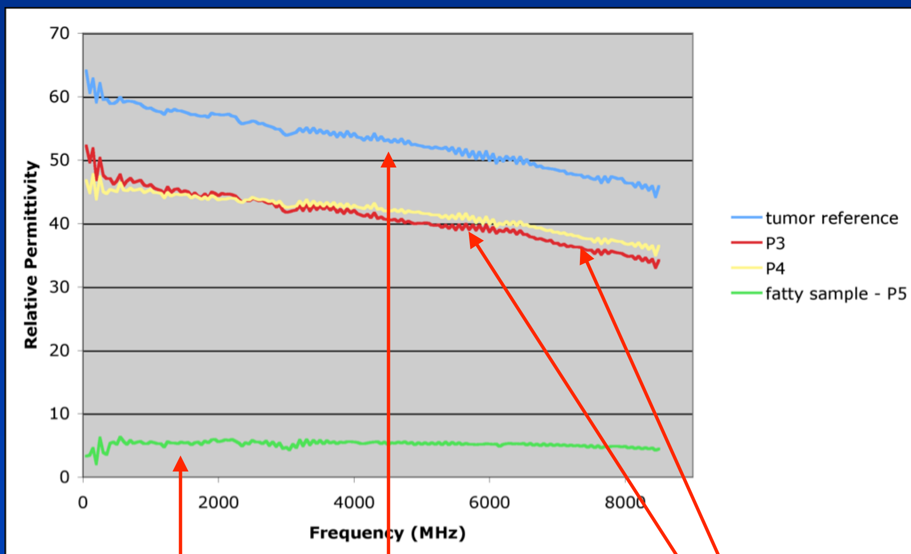
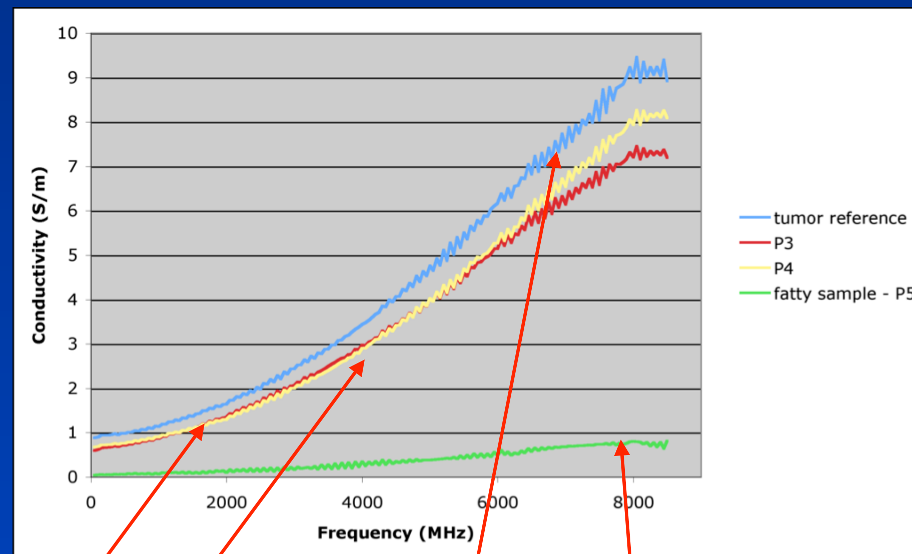
University of Arkansas– October 26-29, 2010

Tissue Properties After Chemo

Permittivity



Conductivity



Tumor

Tissue After Chemo

Tumor

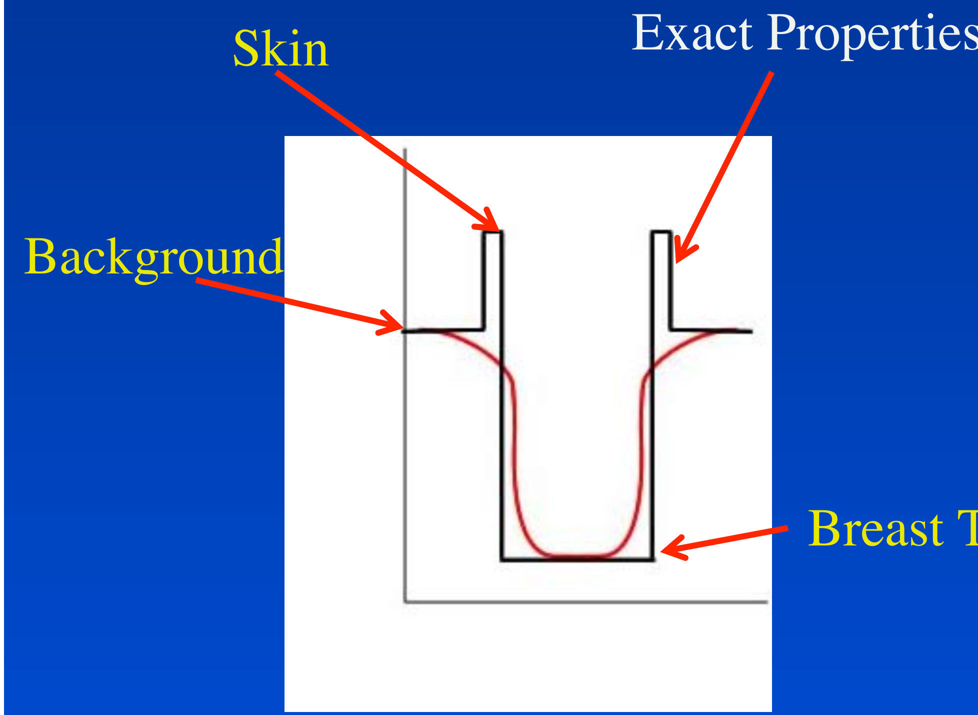
Fat

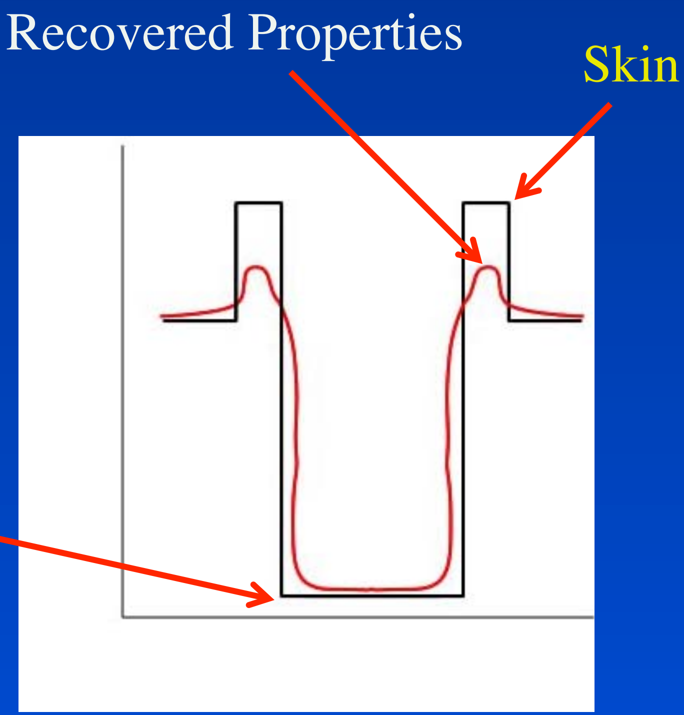
Fat

Implications For Tomography

Smoothing Effects in Microwave Imaging

2D Transects Through Images





Normal Skin – 1-3 mm

Thick Skin – 10 mm

Implications For Tomography

- Typical Skin Thickness – 1 – 3 mm
- Skin Dielectric Properties – $\varepsilon_r = 40.9$ and $\sigma = 0.9$ S/m (1 GHz)
- Electrically Thin – Blends in With Property Gradient Between Coupling Liquid and Breast

- Skin Thickening – Up to 1 cm
- Edema (Saline) Under the Surface
- Electrically Large Enough to be Noticed

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For This Development, We're Looking at Diagnosis

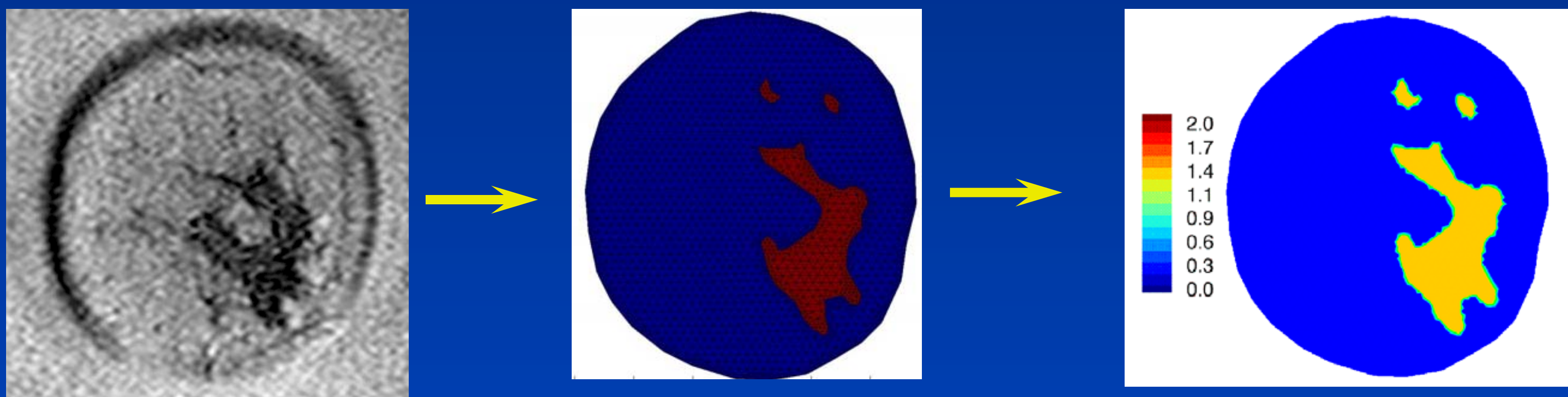
- Key Problem with MR in the Diagnostic Role – Too Many False Positives – Unnecessary Biopsies
- Can We Exploit "Specificity" Aspect of Dielectric Properties?
- Combine Specificity of Microwave with the Resolution of MR?
  – Value Added

Gauss-Newton Iterative Approach: Minimization Statement

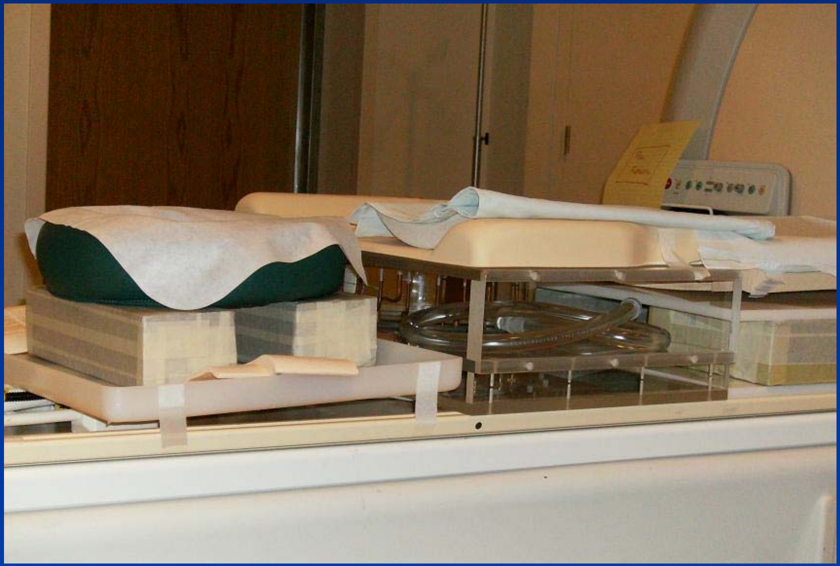
$$\min \left\| \Gamma^m - \Gamma^c(k^2) \right\|_2^2 + \left\| \Phi^m - \Phi^c(k^2) \right\|_2^2 + \lambda \left\| L(k^2 - k_0^2) \right\|_2^2$$

- Log-Magnitudes and Phases
- Soft Prior Regularization – INCORPORATES MR DATA
- Exploits Known Spatial Information

Soft Prior Discussion



- Multi-Region Segmented Meshes
- Weighting Zones with Similar Characteristics
- Can Highlight Suspicious Regions



Four Innovations That Made Integration Possible

- Filters - MR RF – Larmor Frequency
- Serpentine-Shaped Feedlines – Multipath Signals
- Low Profile, Monopole Antennas
- Metal Choice

Low Profile Tank Drives Design Decisions

Conclusion & Future Directions

- Microwave Imaging is for Real
  - Screening, Diagnosis and Therapy Monitoring
  - Good Initial Clinical Data
  - Specificity May be its Real Strength
- Combination with MR is a Real Possibility
- Future Directions –
  - Bone Imaging and Brain Activation Imaging