QUALITATIVE VERSUS QUANTITATIVE APPROACHES TO MICROWAVE-BASED IMAGING TECHNIQUES FOR MEDICAL APPLICATIONS

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THEORIES AND NUMERICS ON INVERSE PROBLEMS
Workshop on Qualitative and Quantitative Approaches to Inverse Scattering Problems
Institute for Mathematical Sciences
National University of Singapore
Singapore, 24 –28 Sep 2018

(From Venezia Biennale Arte 2013
The Encyclopedic Palace)
MOTIVATION

FACT AND QUESTIONS ...

• EARLY 80’s... “MICROWAVES OFFER PROMISES AS IMAGING MODALITY”
  L.E. Larsen and J.H. Jacobi
  (Diagnostic Imaging in Clinical Medicine, 11, 44-47, 1982)

• WHAT EXACTLY MICROWAVES ARE PROMISING OF? AND BY WHEN? REMAIN OPEN QUESTIONS

• INDEED, ALMOST 40 YEARS LATER, MICROWAVES ARE STILL CLAIMING TO OFFER PROMISES... BUT ONLY GAINED A MODEST CLINICAL ACCEPTANCE

• BY THE WAY, THE JOURNEY WAS MORE COMPLICATED THAN EXPECTED BUT THE RESULTS COLLECTED FROM VERY RECENT CLINICAL TRIALS SEEMS SUGGESTING A POSSIBLE EXIT OF THE TUNNEL...

• HOW QUALITATIVE AND QUANTITATIVE IMAGING APPROACHES COMPARE TODAY, AND WHAT ARE THEIR SUPPOSED CHANCES FOR FUTURE PERFORMANCE IMPROVEMENT?
PERSONNAL INVOLVEMENT IN MICROWAVE IMAGING TECHNOLOGY

• MODULATED PROBE ARRAY TECHNOLOGY FOR RAPID NEAR-FIELD TECHNIQUES:
  – MODULATED SCATTERING TECHNIQUE (MST)
  – RAPID CHARACTERIZATION OF RADIATING SYSTEMS (ANTENNA MEASUREMENTS, EMC/EMI TESTING, DOSIMETRY ASSESSMENT, SAR MEASUREMENTS, ETC.)

• FOUNDATION OF THE COMPANY SATIMO (1986)

• DEVELOPMENT AND TECHNOLOGY TRANSFER OF ISM-DEDICATED IMAGING PROTOTYPES:
  – MEDICAL IMAGING (NON-INVASIVE THERMOMETRY)
  – INDUSTRIAL TESTING (CONVEYED PRODUCTS)
  – BURIED OBJECTS (CIVIL ENGINEERING, SECURITY)

• CONTRIBUTION TO COOPERATIVE PROGRAMS:
  – PICASSO WITH UPC BARCELONA (FRANCE/SPAIN)
  – TRANSFERT ET EVALUATION DE PROTOTYPES (TEP, FRANCE)
  – COMAC-BME HYPERThERMIA (EU)
  – EUROPEAN CONCERTED ACTION ON MICROWAVE TOMOGRAPHY (EU, ECAP, MiMed COST)
QUALITATIVE VERSUS QUANTITATIVE APPROACHES TO MICROWAVE-BASED IMAGING TECHNIQUES FOR MEDICAL APPLICATIONS

CONTENT

• INTRODUCTION TO MICROWAVES AND MEDICAL IMAGING
• MICROWAVE-BASED IMAGING FOR MEDICAL APPLICATIONS
  – GENESIS
  – FROM PROJECTION TO TOMOGRAPHY
  – FROM MODELS TO PATIENT BED
• A TEST CASE: BREAST IMAGING
• SO, QUALITATIVE OR QUANTITATIVE?
• SUGGESTIONS AND CONCLUSIONS
MICROWAVES IN THE EM SPECTRUM
(AS A REMINDER)

FREQUENCY (Hz)

WAVELENGTH (m)

MICROWAVES

TV
Radar, Mobiles

INFRA-RED

VISIBLE
Ultraviolet

X rays
Gamma rays

1GHz
1THz
1PHz

30cm
3cm
3mm

1GHz
10GHz
100GHz

MICROWAVES FOR MEDICAL IMAGING
(THIS PRESENTATION)
SIMPLIFIED CLASSIFICATION MAP OF MICROWAVE-BASED APPLICATIONS

- **SENSING**
  - **ACTIVE/PASSIVE**
  - **SHORT RANGE**
  - **LONG RANGE**

- **DIELECTROMETRY**

- **COMMUNICATIONS**

- **POWERING**
  - **TRANSFER/HARVESTING**

*ISM: INDUSTRIAL, SCIENTIFIC, MEDICAL
IS2M: INDUSTRIAL, SCIENTIFIC, SECURITY, MEDICAL*
VARIOUS ASPECTS OF MICROWAVES FOR MEDICAL APPLICATIONS

Industrial
Scientific
Medical

« Low »
power

DIAGNOSIS

BIO-SENSING

HYPER-
THERMIA

IMAGING

ABLATION

« High »
power

THERAPY


TIME LINE OF MAJOR IMAGING MODALITIES
MICROWAVES AS THE “LAST COMER”


...RADIOGRAPHY  MAMMOGRAPHY  CT  CT  DBT  X-rays

...SONAR  US SCAN  US

NMR  NMR SCANNER  MRI

RADAR  1ST DIAG. APPL.  EARLY IMAGING INVESTIGATIONS  MW


EXAMPLES OF EARLY IMAGES OBTAINED WITH DIFFERENT MODALITIES

G. Freiherr, “The Eclectic History of Medical Imaging”, Feature, Nov.06, 2014
## COMPARISON OF MEDICAL IMAGING MODALITIES

<table>
<thead>
<tr>
<th>Modality</th>
<th>Ultrasound</th>
<th>X-ray</th>
<th>CT</th>
<th>MRI</th>
<th>MW</th>
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<tbody>
<tr>
<td>What is imaged</td>
<td>Mechanical properties</td>
<td>Mean tissue</td>
<td>Tissue absorption</td>
<td>Biochemistry (T₁ and T₂)</td>
<td></td>
</tr>
<tr>
<td>Access</td>
<td>Small windows adequate</td>
<td>2 sides needed</td>
<td>Circumferential</td>
<td>Circumferential</td>
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<tr>
<td>Spatial resolution</td>
<td>Frequency and axially</td>
<td>~1 mm</td>
<td>~1 mm</td>
<td>~1 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>dependent 0.3–3 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penetration</td>
<td>Frequency dependent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3–25 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>Very good</td>
<td>Ionizing radiation</td>
<td>Ionizing radiation</td>
<td>Very good</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>100 frames/sec</td>
<td>Minutes</td>
<td>½ minute to minutes</td>
<td>10 frames/sec</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>$</td>
<td>$</td>
<td>$SSSS</td>
<td>$SSSSSSSSS</td>
<td>$SS ??</td>
</tr>
<tr>
<td>Portability</td>
<td>Excellent</td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
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</table>

MICROWAVE IMAGES ARE QUALITATIVELY OR QUANTITATIVELY RELATED TO THE DIELECTRIC PROPERTIES OF TISSUES

DIELECTRIC PROPERTIES DEPEND ON MANY MEDICALLY RELEVANT FACTORS (COMPOSITION, TEMPERATURE, BLOOD FLOW RATE, NORMAL/PATHOLOGICAL, ETC.)

WATER CONTENT HAS A STRONG IMPACT RESULTING IN:
- HIGH DIELECTRIC CONTRASTS BETWEEN LOW/HIGH WATER CONTENT TISSUES
- STRONG SCATTERING AND MULTIPATH PROPAGATION MECHANISMS

THE FREQUENCY DEPENDENCE OF DIELECTRIC PROPERTIES MAY BE OBTAINED VIA:
- PHYSICAL MODELS AND/OR
- EXPERIMENTS (IN VIVO/VITRO)

Penetration depth $L$ (cm)
Wavelength $\lambda$ cm (spatial resolution $\#\lambda/2$)

$$\varepsilon_c = \varepsilon_r - j \sigma(\omega)/\omega = 2\pi f$$

<table>
<thead>
<tr>
<th>$F_{\text{GHz}}$</th>
<th>$\lambda_0$ cm</th>
<th>$\varepsilon'_r$</th>
<th>$\sigma_{s/m}$</th>
<th>$L_{\text{cm}}$</th>
<th>$\lambda_{\text{cm}}$</th>
<th>$\varepsilon'_r$</th>
<th>$\sigma_{s/m}$</th>
<th>$L_{\text{CM}}$</th>
<th>$\lambda_{\text{cm}}$</th>
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<td>0.433</td>
<td>69.3</td>
<td>53</td>
<td>1.43</td>
<td>3</td>
<td>8.5</td>
<td>36</td>
<td>0.72</td>
<td>4.7</td>
<td>10.8</td>
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<tr>
<td>0.915</td>
<td>33.8</td>
<td>51</td>
<td>1.60</td>
<td>2.5</td>
<td>4.4</td>
<td>35</td>
<td>0.73</td>
<td>4.5</td>
<td>5.4</td>
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<tr>
<td>2.450</td>
<td>12.3</td>
<td>49</td>
<td>2.21</td>
<td>1.7</td>
<td>1.8</td>
<td>32</td>
<td>1.32</td>
<td>2.3</td>
<td>2.2</td>
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<tr>
<td>5.800</td>
<td>5.2</td>
<td>43</td>
<td>4.73</td>
<td>0.8</td>
<td>0.8</td>
<td>28</td>
<td>4.07</td>
<td>0.7</td>
<td>1.0</td>
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<tr>
<td>10.00</td>
<td>3.0</td>
<td>40</td>
<td>10.3</td>
<td>0.3</td>
<td>0.5</td>
<td>25</td>
<td>9.08</td>
<td>0.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

$\varepsilon_c$ dielectric constant
$\sigma$ conductivity
$\omega = 2\pi f$

25/09/2018
IMS Workshop, Singapore, Sept.2018
A GLOBAL VIEW ON MEDICAL IMAGING
A MARKET VIEWPOINT

• SALIENT MARKET FEATURES:
  – Market growth supported by the rise of geriatric population and the increased prevalence of CV diseases,
  – Expected Growth Rate: 5.4%, to reach US 35 billions end 2019,
  – X-ray first; fastest growth expected for CT and PET (earlier disease detection),
  – Larger growth expected for emerging markets.
  – Global market shared by only a few big companies.

• KEY GROWTH DRIVERS:
  – Miniaturization and portability,
  – Digitization of measured data,
  – Hybrid imaging systems,
  – Use of non-ionizing modalities
  – Non-invasive and easy-to-use equipment
  – Inexpensive, energy saving, ergonomic medical equipment with low maintenance requirements …

MEDICAL IMAGING EQUIPMENT MARKET
(From: Transparency Market Research, transparencymarketresearch.com)

GLOBAL MEDICAL IMAGING MARKET
(From: Pictures of the Future, Medical Imaging:Facts and Forecasts, siemens.com)

✔ ✔ ✔ ✔ ✔

MICROWAVES AS GOOD CANDIDATE ?
WHAT CLINICAL ACCEPTANCE IS MADE OF?  IMAGE QUALITY... BUT NOT ONLY!

• THE CLINICAL RELEVANCE OF AN IMAGE:
  • DEPENDS ON THE 3-D RESOLUTION PERFORMANCES OF THE IMAGING SYSTEM
  • USUALLY RESULTS FROM AN APPLICATION-DEPENDENT MIX OF ALL ABOVE ISSUES

• CLINICAL ACCEPTANCE
  • IS MORE COMPLICATED AND DEPENDS ON MANY OTHER IMPORTANT ISSUES...
  • ULTIMATELY, REQUIRES SOME MEDICAL ADDED-VALUE RELEVANCE (SPECIFICITY) OR COMPLEMENTARITY WITH OTHER EXISTING MODALITIES
  • MARKET COMPATIBILITY
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• A TEST CASE: BREAST IMAGING
• SO, QUALITATIVE OR QUANTITATIVE ?
• SUGGESTIONS AND CONCLUSIONS
ARCHITECTURE OF GENERIC MW SCANNERS FOR MEDICAL APPLICATIONS (1)

DATA ACQUISITION

- ANTENNA ARRAY
- ARRAY CONTROL

MW T/R UNIT

DATA PROCESSING

- PROCESSORS
- ALGORITHMS

- IMAGE RECONSTRUCTION
  - LINEAR / NON-LINEAR
    - (RADAR)
    - (INVERSE SCATTERING)

- IMAGE: PICTURE OR MAP?
- QUALITATIVE OR QUANTITATIVE?

M. Pastorino, Microwave Imaging, © John Wiley & Sons, 2010
N.K. Nikolova, Introduction to Microwave Imaging, © Cambridge University Press 2017
X. Chen, Computational Methods for Electromagnetic Inverse Scattering, IEEE Press, John Wiley & Sons, 2018
ARCHITECTURE OF GENERIC MW SCANNERS FOR MEDICAL APPLICATIONS (2)

MICROWAVE HARDWARE ASPECT: AN ABUNDANCE OF OPTIONS A CHANCE OR A TRAP?

1. Transmitter/Receiver Unit:
   - Operating frequency band
   - Time/frequency domain
   - VNA single/multi-ports
   - Transceivers (discrete, chips components)
   - etc...

2. Array Arrangement:
   - Mono/Multistatic
   - Geometry: linear/planar, circular/cylindrical, ½ spherical, conformal...
   - Number of elements, position
   - Series/parallel addressing
   - etc...

3. Antenna element:
   - Mono/dipole, slots patch, vivaldi, dielectric filled waveguides, cavity backed, etc...
   - Single/dual polarization
   - Contact / Contactless / Shielded
   - etc...


PRINCIPLE OF IMAGE RECONSTRUCTION FOR MICROWAVE-BASED MEDICAL APPLICATIONS

QUALITATIVE AND QUANTITATIVE APPROACHES TO INVERSE SCATTERING PROBLEMS

MICROWAVE INTERROGATION (INCIDENT FIELD)

TARGET

\[ \varepsilon_c(P) = \varepsilon_r(P) - j\sigma(P;\omega) \]

EQUIVALENT CURRENT PICTURE

INVERSE SOURCE PROBLEM

LINEAR (ALGEBRAIC/FT) QUALITATIVE IMAGING OPERATOR DEPENDENT

INDUCED CURRENTS \( J_{eq}(P) \)

RESPONSE (SCATTERED FIELD)

DIELECTRIC PERMITTIVITY MAP

INVERSE SCATTERING PROBLEM

NON LINEAR (ITERATIVE) QUANTITATIVE IMAGING OPERATOR INDEPENDENT
SIMPLIFIED FAMILY TREE OF RECONSTRUCTION ALGORITHMS

QUANTITATIVE IMAGING

NON-LINEAR ITERATIVE RECONSTRUCTION

MODEL BASED APPROACH
OPTIMIZATION TECHNIQUES
(CG, SA, GA)

INVERSE SCATTERING

STRONG SCATTERING

EM MODEL

QUALITATIVE IMAGING

LINEAR RECONSTRUCTION

SPECTRAL (FOURIER) DECONVOLUTION (PSF)

DAS, BEAM FORMING SIGNAL PROCESSING ETC.

INVERSE SOURCE PROBLEM

“HOT-SPOT” MODEL

RADAR APPROACH

WEAK SCATTERING

IMS Workshop, Singapore, Sept. 2018
MW FOR MEDICAL DIAGNOSTIC APPLICATIONS
SIGNIFICANT MILESTONES

**APPLICATIONS**

**STEPS IN IMAGE RECONSTRUCTION ALGORITHMS**

1. **Step 1**
   - Time Domain Spectroscopy & Diffraction Tomography
   - Imaging Systems Geometry:
     - single-port sensors
     - mechanical scan
     - planar
     - electronic scan
     - circular
     - cylindrical
     - ½ spherical, cubic, conformal...

2. **Step 2**
   - Non-linear Iterative Reconstruction (model-based)

3. **Step 3**
   - UWB Radar Processing

4. **Step 4**
   - Time-Reversal

5. **Step 5**
   - ..... (not fully visible)

**EARLY DIAGNOSTIC**

- **1980**
  - Vital Life signs, organ mvts., lung disease, ...
  - dosimetry

- **1990**
  - NIT/1
  - biological/animal targets

- **2000**
  - NIT/2
  - breast/brain/bone...

- **2010**
  - NIT/3
  - imaging

**CONTINUOUS INVESTIGATIONS & EARLY (PRE) CLINICAL TRIALS**

- EARLY IMAGING INVESTIGATIONS
  - mesoslicks
  - NIT/1
  - biological/animal targets

**APPLIED**

- Vital life signs, organ mvts., lung disease, ...
- dosimetry

**1. Discovering a new continent**

**2: Starting its exploitation**

**25/09/2018 IMS Workshop, Singapore, Sept.2018**

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EXAMPLES OF EARLY ARRANGEMENTS FOR MICROWAVE TOMOGRAPHY

- **Planar Transmitting Array 2-4 GHz**
  - **Fixed Target**
  - **(Walter Reed Army Institute, 1980)**

- **Plane Wave Transmitter 2.45 GHz**
  - **Fixed Target**
  - **(SUPELEC, 1983)**

- **Transmitting Antenna 915 MHz**
  - **Translation**
  - **Rotation**
  - **Fixed Target**
  - **(Shinzu Univ, 1987)**

- **Circular Array of T/R Antennas 2.33 GHz**
  - **Fixed Target**
  - **(UPC Barcelona, 1985)**
FIRST MICROWAVE IMAGES OF PERFUSED ORGANS (1)
RASTER SCAN TRANSMISSION IMAGING (WRAI, 1979)

MECHANICAL RASTER SCAN:
- IMMERSION TECHNIQUE
- 64x64 POINTS
- SAMPLING: 1.4 mm
- DURATION: 4.5 HOURS

FIRST MICROWAVE IMAGES OF PERFUSED ORGANS (2)
TOWARD PHASED ARRAY TECHNOLOGY... (WRAI, 1986)

Tx/Rx PLANAR ARRAYS,
POSSIBILITY FOR CONFOCAL IMAGING
HEXAGONAL LATTICE, SAMPLING: 12.7 – 15.2mm
ELECTROMECHANICAL SWITCHING
EXPECTED ACQUISITION TIME: 3.5 min.


A PERSISTING MYSTERY:
NO PUBLISH RESULT!
FIRST REAL-TIME HUMAN IMAGES (1)
MW TOMOGRAPHY OF BIOLOGICAL TARGETS (SUPELEC, 1982-2000)

LINEAR MODULATED SCATTERING TECHNIQUE PROBE ARRAY


2.45 GHz MST-BASED MICROWAVE CAMERA
2D RETINA / COLLECTOR ARRANGEMENT

FIRST MICROWAVE IMAGES SENSITIVE TO BLOOD FLOW RATE AND TEMPERATURE

**IN VIVO IMAGERY (FOREARM, HAND)**

![Microwave Imaging](image1)

*(Laboratoire de Thermobiologie, Strasbourg, TEP Procedure, 1987)*

**MW IMAGE SENSITIVITY TO BLOOD FLOW RATE**

![Microwave Imaging](image2)


**MW IMAGE SENSITIVITY TO TEMPERATURE**

![Microwave Imaging](image3)


**CAPACITIVE HEATING @ 13.56 MHz**

![Capacitive Heating](image4)

*(Institut Curie, Paris, TEP Procedure, 1987)*

**IN VIVO IMAGERY (FOREARM, HAND)**

![Microwave Imaging](image5)

THE FIRST ATTEMPT OF PRE-CLINICAL ASSESSMENT: NON INVASIVE THERMOMETRY...

- NIT: A CRUCIAL ISSUE FOR HYPERTHERMIA TREATMENT EFFICACY

- COMPETING MODALITIES (ca 1985):
  - X-RAYS CT
  - MRI
  - ULTRA-SOUND
  - ELECTRICAL IMPEDANCE TOMOGRAPHY
  - MICROWAVES: ACTIVE & PASSIVE

- MICROWAVE CAMERA (ca 1990):
  - SUCCESSFULL ON-PHANTOM RESULTS
  - FAILS TO BE INTEGRATED IN HYPERTHERMIA EQUIPMENT

- MAJOR (NOW CLEAR) EXPLANATIONS:
  - SINGLE VIEW/ SINGLE FREQUENCY,
  - LINEAR DT RECONSTRUCTION
  - BOLUS ARRANGEMENTS
  - LOW COMPUTING POWER

* TWO MAJOR REQUIREMENTS TO IMPROVE IMAGE QUALITY:
  - NON-LINEAR RECONSTRUCTION
  - MULTIVIEW INTERROGATION

* BUT, AN EVIDENT LACK OF COMPUTING POWER!
THE FIRST MICROWAVE SCANNER
UPC BARCELONA, 1990

INVERSE PROBLEM AS A SEQUENCE OF DIRECT PROBLEMS
APPLICATION TO ITERATIVE TOMOGRAPHIC RECONSTRUCTION
(AND SAR MEASUREMENT)

DIRECT PROBLEM SOLVER

\[ C_n = C_{n-1} + \Delta C \]

\[ S^{-1} \]

\[ \Delta E_{sca} = S\Delta C \]

SAR

INVERSE SCATTERING:
An Iterative Numerical Method for Electromagnetic Imaging

RECONSTRUCTION OF TWO-DIMENSIONAL PERMITTIVITY DISTRIBUTION USING THE DISTORTED BORN ITERATIVE METHOD


LIMB MICROWAVE IMAGING @ 1.2 GHz
EXAMPLE OF PATIENT-TO-PATIENT SENSITIVITY AND ALGORITHM DEPENDENCE

2015 REVIEW OF MiMed CONTRIBUTIONS (*)

From Computer... To Patient Bed... A “LOSSY” PATH...

<table>
<thead>
<tr>
<th>Application</th>
<th>Algorithm [ref]</th>
<th>Numerical</th>
<th>Experimental</th>
<th>Human/Animal</th>
<th>Clinical Trial</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heartbeat</td>
<td>Doppler Theorem [7], [8]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>2.4 GHz, 5.8 GHz, 10 GHz</td>
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<tr>
<td>Blood Flow/Pressure</td>
<td>Transmission meas. [57], [58]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>2.5 GHz, 0.1-5 GHz</td>
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<tr>
<td>Cerebral Edema</td>
<td>Transmission meas. [5]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Brain Stroke</td>
<td>Transmission meas. [6]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>0.3-3 GHz</td>
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<tr>
<td>Water Accumulation</td>
<td>Reflection meas. [60], [59]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>915 MHz, 920 MHz, 3.1-10.6 GHz</td>
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<td>Brain Imaging</td>
<td>Newton-type [4], [40]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Diff. Single freq. in 0.5-2.5 GHz</td>
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<td>Born Iterative [61]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>600, 850, 1000 MHz</td>
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<td>Gauss-Newton [65]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>1 GHz</td>
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<tr>
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<td>Confocal [55], [62]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<td>Breast Imaging</td>
<td>Confocal [68], [69]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>3.1-10.6 GHz</td>
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<td>TSAR [54], [70]</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
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<td>Space-time Beamforming [71]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
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<td>Two stage Capon Beamforming [72]</td>
<td>Yes</td>
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<td>No</td>
<td>No</td>
<td>UWB</td>
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<td>Newton-type [73], [74]</td>
<td>No</td>
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<td>Yes</td>
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<td>Single freq. in 300-900 MHz, 2 GHz</td>
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<td>Conjugate Gradient Method [75]</td>
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<td>Gauss-Newton [65]</td>
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<td>No</td>
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<td>1 GHz</td>
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<td>DBIM [77]</td>
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<td>No</td>
<td>No</td>
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<td>CSI [78]</td>
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<td>No</td>
<td>No</td>
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<tr>
<td>Bone Imaging</td>
<td>Levenberg-Marquadt [9]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>800 MHz</td>
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<td>Gauss-Newton [10]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Soft-Tissue</td>
<td>Newton/MR-CSI [57]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>1 GHz</td>
</tr>
<tr>
<td></td>
<td>TSAR [17]</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>50 Mz - 13.51 GHz</td>
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<tr>
<td>Heart Imaging</td>
<td>MGM [12], [14]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>0.9 GHz</td>
</tr>
<tr>
<td></td>
<td>Back-Projection [15], [16]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>0.8-3 GHz</td>
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<tr>
<td>Arm Imaging</td>
<td>CSI [81]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>0.8, 1, 1.2 GHz</td>
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<td></td>
<td>Gauss-Newton [65]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>2.33 GHz</td>
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<td></td>
<td>Newton-Kantorovich [82]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>434 MHz</td>
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<td>Thorax</td>
<td>Newton-Kantorovich [82]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>434 MHz</td>
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<td>Localization</td>
<td>Levenberg-Marquadt [83]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>403.5 MHz</td>
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<tr>
<td>Whole-Body (Dog)</td>
<td>3-D Gradient [84]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>0.9 GHz</td>
</tr>
<tr>
<td>Leg (Pig)</td>
<td>Newton Gradient, MR-CSI [37]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>0.9-2.05 GHz</td>
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MICROWAVE SCANNERS FOR BIOMEDICAL ASSESSMENT
SOME EXAMPLES...

Carolinas Heart Inst (USA).

Keele Univ. (UK)

Univ. of Calgary (CA)

INVERSE SCATTERING

RADAR
MULTI-VIEW
MONO-VIEW

1990
1995
2000
2005
2010
2015

human forearm

NIT on animal

breast imaging volunteers/patients

UPC Barcelona (SP)

Thayer School of Engng. Dartmouth (USA)

Univ. of Bristol

McGill Univ.

F=2.3GHz
N=64

F=0.3-3GHz
N=16

F=2-4GHz
N=16

F=2.45GHz
Nt=Nr=32

F=1GHz
N=32

F=1-2.3GHz
N=24

F=50MHz-15GHz
N=1

F=4-8GHz
N=60
QUALITATIVE VERSUS QUANTITATIVE APPROACHES TO MICROWAVE-BASED IMAGING TECHNIQUES FOR MEDICAL APPLICATIONS

CONTENT

• INTRODUCTION TO MICROWAVES AND MEDICAL IMAGING
• MICROWAVE-BASED IMAGING FOR MEDICAL APPLICATIONS
  – GENESIS
  – FROM PROJECTION TO TOMOGRAPHY
  – FROM MODELS TO PATIENT BED
• A TEST CASE: BREAST IMAGING
• SO, QUALITATIVE OR QUANTITATIVE ?
• SUGGESTIONS AND CONCLUSIONS
MICROWAVE-BASED BREAST IMAGING (1)

- DIELECTRIC IMAGING – AN ALTERNATIVE TO X-RAY MAMMOGRAPHY, A.W. PREECE ET AL., 1991

- DIFFERENT POSSIBLE APPLICATIONS: SCREENING, DIAGNOSIS, TREATMENT MONITORING

- BREAST: A COMPLEX DIELECTRIC TARGET BY ITSELF (FIBRO-GLANDULAR/ADIPOSE TISSUES, CHEST WALL, SKIN...), FURTHERMORE SUBJECT TO A LARGE VARIABILITY

- EXPECTED “LARGE” CONTRASTS BETWEEN HEALTHY AND TUMORAL TISSUES... SUBJECT TO DEBATE!

- BOTH QUALITATIVE (RADAR, HOLOGRAPHY) AND QUANTITATIVE (INVERSE SCATTERING) APPROACHES

![Image of breast structure with labels for different tissues]
MICROWAVE-BASED BREAST IMAGING (2)

• A MAJOR SOURCE OF INSPIRATION FOR THE MICROWAVE COMMUNITY
  (e.g. Mimed COST ACTION: 200 academic and industry contributors from 30 participating and associated countries)

• EXPLOITATION OF THE CONTINUOUSLY GROWING COMPUTER POWER FOR:
  • DIELECTRIC CHARACTERIZATION
  • MRI-BASED NUMERICAL MODELS AND 3D-PRINTED PHANTOMS
  • ANTENNA DESIGN AND OPTIMIZATION ATTEMPTS
  • FREQUENCY/TIME DOMAIN RECEIVERS SIMULATION
  • MANY SCANNER GEOMETRIES
  • RECONSTRUCTION ALGORITHMS QUALITATIVE AND QUANTITATIVE
  • SENSITIVITY ANALYSIS THANKS TO DATA STEMMING FROM NUMERICAL MODELS AND PHANTOMS

• CRITICAL LACK OF COMPARISON BETWEEN DIFFERENT SETUPS, ALGORITHMS...

• MANY REFERENCE BOOKS AND REVIEW PAPERS AVAILABLE!
EXAMPLES OF BREAST IMAGING SYSTEMS
FOR VOLUNTEER/ PATIENT INVESTIGATIONS (1)

**MONOSTATIC UWB RADAR**

*FREQ. RANGE: 1.5 TO 8 GHz*

*1 ANTENNA, FULL MECH.SCAN (BALANCED ANTIPODAL VIVALDI)*

*ARBITRARY SCAN SURFACE WITH NORMAL TO SKIN PROBE TILT LASER SENSOR (SKIN REMOVAL)*

(Courtesy J. Bourqui, Univ. Calgary)

**MULTISTATIC TOMOGRAPHY**

*MONO-FREQ. FROM 0.5 TO 2 GHZ CYLINDRICAL, 16 ANTENNAS (VERTICAL MONOPOLES)*

*MEDIUM IMMERSED BREAST VERTICAL MEC. SCAN THE LARGEST NUMBER OF EXAMS SINCE 1995 (FEW HUNDREDS)*

(Courtesy P. Meaney Microwave Imaging Syst. Tech. Inc.)

**MULTISTATIC RADAR**

*UWB FROM 1.5 TO 8 GHz*

*½ SPHERICAL, 60 ANTENNAS (CAVITY-BACKED SLOTS)*

*SOLID MATCHING MEDIUM FOR SKIN CONTACT SMALL ROTATION (SKIN REMOVAL)*

(Micrima Ltd. 2016)

Copyright © Micrima Ltd. 2016

(Courtesy J. Bourqui, Univ. Calgary)

(Courtesy P. Meaney Microwave Imaging Syst. Tech. Inc.)
EXAMPLES OF BREAST IMAGING SYSTEMS FOR VOLUNTEER/PATIENT INVESTIGATIONS (2)

IN-VIVO MEASUREMENT OF DIELECTRIC PERMITTIVITY

“PERSONNALIZED” RESPONSE MONITORING

(Courtesy University of Calgary)

(Courtesy of McGill University)
RECENT UWB RADAR CLINICAL RESULTS PRESENTED BY MICRIMA

Representative 3D data set from MARIA system, showing location of high contrast regions that correspond to areas of abnormal radio frequency scattering attributable to the presence of lesions in the breast. The hemispherical display axes which correspond to the physical shape of the scanning head. (References: Micrima Limited)


Table:

<table>
<thead>
<tr>
<th>Results</th>
<th>Cases</th>
<th>Sensitivity Score (%)</th>
<th>Mean Age (Years)</th>
<th>Age Range</th>
<th>Cysts Ss</th>
<th>Cancer Ss</th>
<th>Other Ss</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>150</td>
<td>119 (79%)</td>
<td>52.5</td>
<td>16-89</td>
<td>42/54 (75%)</td>
<td>45/59 (75%)</td>
<td>29/60 (81%)</td>
</tr>
<tr>
<td>Pre-/ Peri-</td>
<td>107</td>
<td>83 (76%)</td>
<td>38.0</td>
<td>16-60</td>
<td>36/48 (75%)</td>
<td>25/27 (85%)</td>
<td>26/32 (81%)</td>
</tr>
<tr>
<td>Post</td>
<td>41</td>
<td>36 (88%)</td>
<td>69.0</td>
<td>49-89</td>
<td>6/6 (100%)</td>
<td>27/33 (82%)</td>
<td>3/4 (75%)</td>
</tr>
<tr>
<td>Lucent</td>
<td>38</td>
<td>28 (74%)</td>
<td>64.5</td>
<td>40-89</td>
<td>3/5 (60%)</td>
<td>21/29 (72%)</td>
<td>4/4 (100%)</td>
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<tr>
<td>Dense</td>
<td>83</td>
<td>63 (76%)</td>
<td>50.0</td>
<td>19-81</td>
<td>33/41 (80%)</td>
<td>19/21 (90%)</td>
<td>15/19 (79%)</td>
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<tr>
<td>Unknown</td>
<td>29</td>
<td>25 (86%)</td>
<td>48.5</td>
<td>16-81</td>
<td>6/8 (75%)</td>
<td>10/10 (100%)</td>
<td>10/13 (77%)</td>
</tr>
</tbody>
</table>

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RECENT INVERSE SCATTERING CLINICAL RESULTS PRESENTED BY MIST

NEoadjuvant Chemotherapy Monitoring

QUALITATIVE VERSUS QUANTITATIVE APPROACHES TO MICROWAVE-BASED IMAGING TECHNIQUES FOR MEDICAL APPLICATIONS

CONTENT

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  – GENESIS
  – FROM PROJECTION TO TOMOGRAPHY
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• A TEST CASE: BREAST IMAGING
• SO, QUALITATIVE OR QUANTITATIVE?
SUGGESTIONS AND CONCLUSIONS
QUALITATIVE OR QUANTITATIVE?

- QUANTITATIVE IMAGING IS BASED ON AN EXACT FORMULATION, BUT...
  - REQUIRES COMPLICATED COMPUTATION (FORWARD PROBLEM) EVEN FOR SIMPLIFIED MODELS
  - OFTEN INTRODUCES MODEL ERRORS (INTERACTIONS, COUPLING, ETC.)
  - A PRIORI INFORMATION USUALLY NEEDED (ALGORITHM CONVERGENCE)
  - LOW SPATIAL RESOLUTION (COMPUTER LIMITATION TO LOW FREQ.)
  - IS ONLY QUANTITATIVE WITH RESPECT TO THE DIELECTRIC PERMITTIVITY
  - THE IMAGE NEEDS TO BE TRANSLATED IN TERMS OF CLINICAL EFFECTS

- QUALITATIVE IMAGING IS APPROXIMATE, BUT...
  - DOES NOT REQUIRE COMPLICATED COMPUTATION
  - NEGLIGHTS ANTENNAS/PATIENT INTERACTIONS
  - ONLY WEAK A PRIORI INFORMATION NEEDED
  - GOOD SPATIAL RESOLUTION
  - SENSITIVE TO CHANGES OF TISSUE DISTRIBUTION

CONSEQUENTLY, NEITHER QUANTITATIVE NOR QUALITATIVE MICROWAVE IMAGING APPROACHES CURRENTLY EXHIBITS AN EVIDENT ADVANTAGE IN TERMS OF CLINICAL ACCEPTANCE
WHERE ARE WE IN THE MICROWAVE IMAGING DEVELOPMENT FLOWCHART

“INSIDE” MICROWAVE COMMUNITY

MICROWAVE EXPERTISE (HARD/SOFTWARE) & SUPPOSED SPECIFIC ADVANTAGES OF MICROWAVES (DIELECTRIC PROPERTIES)
« Technology» pull

“OUTSIDE” MICROWAVE COMMUNITY

CLINICAL NEEDS

« MAJOR » HEALTH ISSUES

EXISTING MODALITIES

« Market » push

CLINICAL ASSESSMENT

INTER-COMPARISON MULTI-MODALITY LARGE SCALE VALIDATION

CLINICAL ACCEPTANCE & PRACTICE

ACCESS TO MARKET

TARGET ADJUSTMENT

PROTO REVISION

Encouraging results...

EARLY PROOF OF CONCEPT NUMERICAL SIMULATION ON-PHANTOM EXPERIMENT

PROTO TYPE TEST CASES PRE-CLINICAL

NO

PERF/COST BENEFIT

YES

IDENTIFIED TARGET

Good candidate...

CLINICAL NEEDS

Technology transfer

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WHERE ARE WE? THE ICEBERG METAPHOR...

OUTCOME

A FEW OPERATIONAL SYSTEMS ENGAGED IN CLINICAL TRIALS:
- "ENCOURAGING" RESULTS FROM EARLY OUTCOMES
- SPECIFICITY TO VALIDATE

EFFORTS

NUMERICAL MODELING:
- ALGORITHM REFINEMENT,
- TISSUE CHARACTERIZATION,
- PROTOTYPE DEVELOPMENT,
- PHANTOM EXPERIMENT,
- ETC...ETC...ETC...

WHAT CAN BE DONE?

BETTER USING AVAILABLE MICROWAVE TECHNOLOGY
BEING PATIENT...
WAITING AND ANTICIPATING FOR INCREASED COMPUTER POWER
RETURNING TO BASIC MW/BIO INTERACTIONS
INCREASING INTERACTION WITH MEDICAL COMMUNITY

25/09/2018 IMS Workshop, Singapore, Sept.2018
TO SUMMARIZE... (1)
ONE COULD HAVE BEEN SEEMING THAT MICROWAVES HAD REACHED THEIR LIMITS

* LACK OF IMAGE ROBUSTNESS
  * ALGORITHM DEPENDENCE: INACCURATE AND/OR ILL-CONDITIONED MODEL-BASED
  * ARTEFACTS: PATIENT COMPLEXITY-VARIABILITY / PATIENT-SYSTEM INTERACTIONS
  * NOT FULLY “SELF-SUFFICIENT” EXCEPT FOR LOG-TRANSFORM INVERSION
    * NEED FOR A PRIORI INFORMATION
    * RADAR: SKIN PROFILE (LASER), AVERAGED WAVE VELOCITY (MW TRANSMISSION)
    * INVERSE SCATTERING: SHAPE (LASER, MOULDING), REGIONAL/AVERAGED DIELECTRIC PERMITTIVITY FROM OTHER IMAGING MODALITIES (MW MONOSTATIC RADAR, MRI, X-RAYS...)

* INSUFFICIENT SENSITIVITY/ DYNAMIC RANGE
  * CONTRAST AGENTS (ACCEPTANCE, SPECIFICITY, MODULATION TECHNIQUE)
  * DIFFERENTIAL IMAGING (LINEARIZATION, INCREASED DYNAMIC RANGE)

* QUESTIONABLE CLINICAL RELEVANCE
  * LOW IMAGE QUALITY
    * ARTEFACTS, CLUTTER
    * LOCALIZATION INACCURACIES
    * LOW SPATIAL RESOLUTION
  * QUESTIONABLE SPECIFICITY TO BE VALIDATED
  * VERY FEW PAPERS IN MEDICAL JOURNALS...

STILL LOW BUT GROWING CLINICAL ATTRACTIVITY
TO SUMMARIZE (2)
FORTUNATELY, THERE IS SOME SPACE FOR IMPROVEMENT...

• EXPLOITING AVAILABLE MICROWAVE TECHNOLOGY FOR “BETTER” DATA
  – RADAR-BASED IMAGING: INTRODUCING THE BEST OF WIRELESS TECHNOLOGY
    AVAILABLE FOR COMMUNICATION SYSTEMS AND BIO-SENSORS
    (MODULATION AND PROCESSING SCHEMES: RFID, MIMO, OFDM, GPS...)
  – INVERSE SCATTERING IMAGING: MORE INDEPENDENT DATA SETS (NUMBER, QUALITY)
  – NOVEL SYSTEM ARCHITECTURES (SERIES/PARALLEL; WIRED/WIRELESS; ETC.)
  – FROM DISCRETE COMPONENTS TO IC CHIPS, INTEGRATED TRANSCEIVERS, ...

• WAITING AND ANTICIPATING FOR INCREASED COMPUTER POWER...
  – RADAR: TOWARD REAL-TIME
  – INVERSE-SCATTERING IMAGING: DECREASING MODEL NOISE, FULL 3D MODELING
    INCLUDING INTERACTIONS AND MUTUAL COUPLING...
  – USING OTHER IMAGING MODALITIES FOR A PRIORI INFORMATION AND FUSION
    PURPOSES
  – CONSIDERING NON IMAGING-BASED PROTOCOLS (SENSOR NETWORKS,
    CLASSIFICATION, ETC.)
TO SUMMARIZE (3)
FORTUNATELY, THERE IS SOME SPACE FOR IMPROVEMENT (Contd)

• RETURNING TO BASIC MW/BIO INVESTIGATIONS
  – TISSUE DIELECTRIC CHARACTERIZATION (LOCAL PROBE, MRI)
  – HIGH RESOLUTION MW SCANNING MICROSCOPY
  – PHYSICAL OR HEURISTIC MODELS FOR FREQUENCY DEPENDENCE
  – MW DIELECTRIC SPECIFICITY AND SENSITIVITY ASSESSMENTS

• INCREASING INTERACTIONS WITH MEDICAL COMMUNITY
  – LOOKING FOR MORE MICROWAVE- FRIENDLY AND CLINICALLY RELEVANT SCENARIOS
  – TECHNICAL ADVANCES MUST BE GUIDED BY CLINICAL RETURNS
  – CLINICAL ASSESMENT AND VALIDATION WILL REQUIRE A LONG TERM EFFORT...
ACKNOWLEDGEMENTS

for sharing feelings, information and experience...

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- D. Smith, M. Sarafianou (Micrima)
- N. Nikolova (Mc Master University)
- T. Henriksson (Univ. of Bristol)
- P. Kosmas (King’s College)
- L. Crocco (CNR, IREA)
- G. Vecchi (Polytechnico, Torino)
- ... many others
EM TENSOR RECRUITMENT OFFER

http://emtensor.com/careers/

EMTensor GmbH is a medical device company based in Vienna, Austria, focused on R&D and commercialization of novel electromagnetic (microwave) imaging devices. We have an extensive IP portfolio, twenty years of internationally recognized R&D and secure financial backing. We are an enthusiastic small team which is moving forward in big steps. Therefore, we are looking for a new team member who is as passionate as we are in all what he/she does and who will work together with us in order to achieve our common goals.

Software Development / IT Engineer

Your main role and responsibilities:
- Become part of the EMTensor team.
- Maintain and further develop our (parallel) in-house software.
- Work closely with our computational team.

Your profile:
- IT degree with specialization in Scientific Computing / Software Development.
- Experience in C++ and distributed-memory parallelization with MPI.
- Unix shell & python scripting.
- Excellent English level, both writing and speaking.
- High team spirit.

Computational Engineer / Researcher

Role and responsibilities:
- Development of algorithms for image reconstruction, including electromagnetic wave propagation and inverse problems.

Qualifications and experience:
- PhD in Computational Engineering, Applied Mathematics or Computer Science.
- Experience in C++ and distributed-memory parallelization with MPI.
- Knowledge of numerical methods for solving electromagnetic problems (FDTD, FEM, ...).
- Good German and English level, both writing and speaking.
Microwaves for medical imaging: Some possible pathways for an accelerated progress towards clinical practice

Lorenzo Crocco, National Research Council, Napoli, Italy
DOI: http://dx.doi.org/10.1016/j.nhtm.2014.11.026

Abstract
The talk will start from a brief review of the physical basis of microwave imaging for medical diagnostics and of the challenges that have to be faced in this technology, to present three areas which are possibly the most promising ones for a fruitful application of microwave imaging in the medical arena.

**The first one is the monitoring of brain injuries**, which is a topic of increasing importance for its impact on the European health system in the ageing society. In particular, it will be discussed how microwave imaging can play a role both in the detection of the diseases in the early stage and in their clinical follow-up, by filling the gap between current diagnostic modalities and the need of continuous monitoring at the patient's bed.

**The second one is the potential of enhancing the capabilities of microwave imaging by means of contrast agents.** Indeed, while contrast enhancement is a common practice to improve performances in medical imaging, it presents even some remarkable and specific advantages in microwave imaging, provided suitable contrast agents are adopted.

**Third, and not last**, the intrinsically dual nature of microwaves, which are not only a diagnostic tool, but also a therapeutic means (hyperthermia, thermo-ablation), makes them a suitable candidate to address the emerging paradigm of theranostics, wherein the imaging capability provide the basis for truly patient specific treatments.
Target Audience
- Hospitals and Clinics
- Research Institutes and Contract Research Organizations
- Manufacturing Companies
- Clinical Laboratories
- Market Research and Consulting Firms
- Breast Imaging Software Providers
- Medical Device Distributors and Suppliers

Scope of the Report
- This research report categorizes the breast imaging market into the following segments:

Global Breast Imaging Market, by Technologies
- Ionizing Breast Imaging Technologies
  - Analog Mammography
  - Full-Field Digital Mammography (FFDM)
  - 3D Breast Tomosynthesis
  - Positron Emission Tomography/Computed Tomography (PET/CT)
  - Molecular Breast Imaging/Breast-Specific Gamma Imaging (MBI/BSGI)
  - Cone Beam Computed Tomography (CBCT)
  - Positron Emission Mammography (PEM)
  - Electric Impedance Tomography
  - Non-Ionizing Breast Imaging Technologies Market
  - Breast MRI
  - Breast Ultrasound
  - Optical Imaging
  - Whole Breast Ultrasound
  - Breast thermography

Global Breast Imaging Market, by Region
- North America
  - U.S.
  - Canada
  - Europe
  - Germany
  - France
  - U.K.
  - Rest of Europe
  - Asia-Pacific
  - Japan
  - China
  - India
  - Rest of Asia-Pacific
  - Rest of the World

Available Customizations
- With the given market data, MarketsandMarkets offers customizations as per the company’s specific needs. The following customization options are available for global breast imaging market report:
  - Product Analysis
  - Product Matrix, which gives a detailed comparison of the product portfolios of the top five companies
  - Geographical Analysis
  - Further breakdown of the RoW breast imaging market into the Middle East, Latin America, and Africa
  - Company Information
  - Detailed analysis and profiling of additional market players (Up to 5)
FIRST ATTEMPTS TO OBTAIN MICROWAVE IMAGES OF ISOLATED ORGANS

POINT SPREAD FUNCTION 3cm/div   2 SMALL SPHERES

Trans. plane   Long. plane  Trans. plane   Long. plane