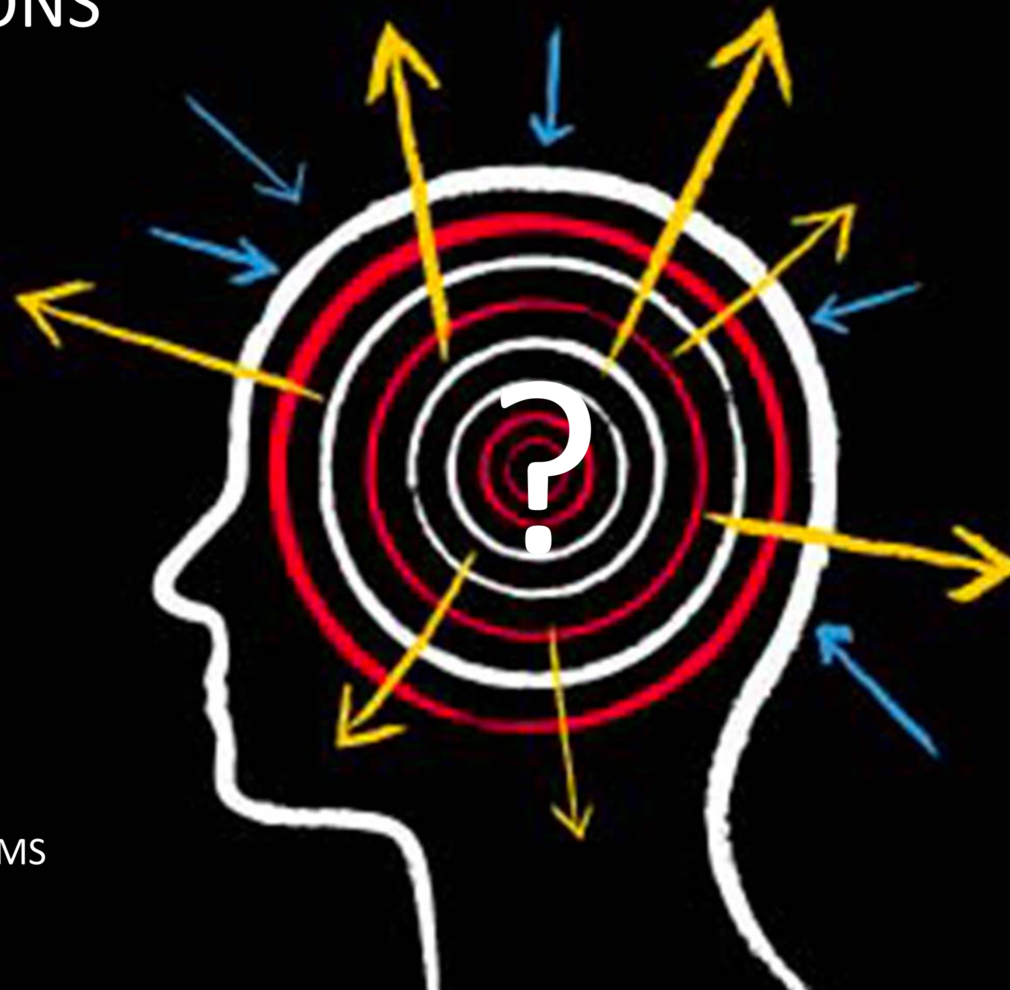
QUALITATIVE VERSUS QUANTITATIVE APPROACHES TO MICROWAVE-BASED IMAGING TECHNIQUES FOR MEDICAL APPLICATIONS

Jean-Charles Bolomey
Emeritus Professor
University Paris Sud, France
jch.bolomey @ gmail.com



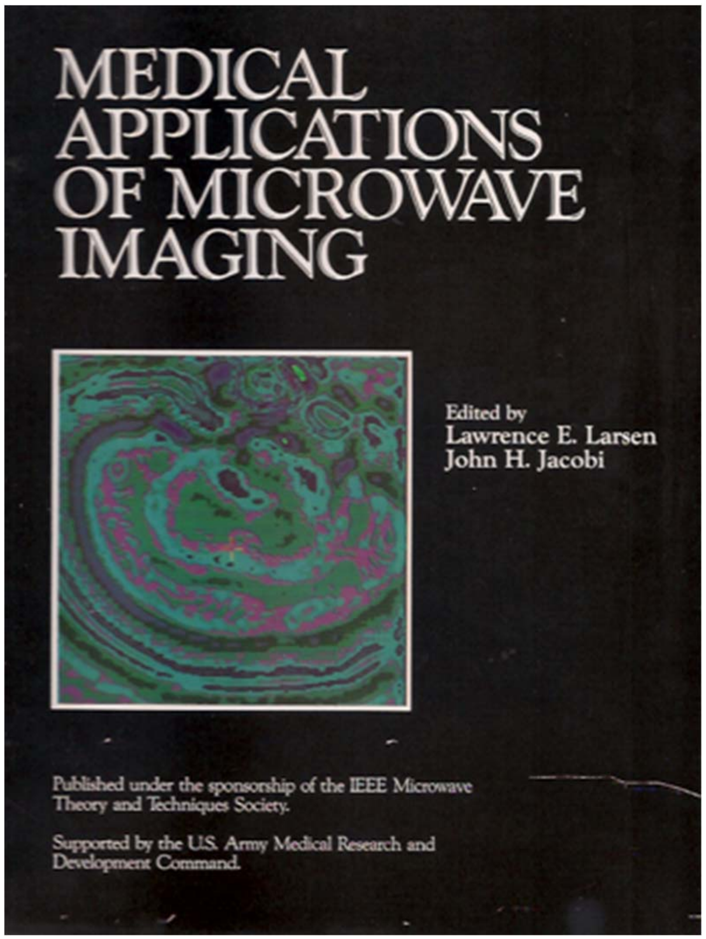
THEORIES AND NUMERICS ON INVERSE PROBLEMS

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)*

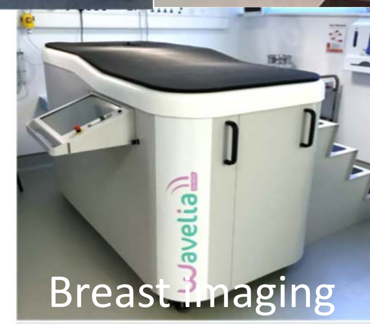
MOTIVATION
FACT AND QUESTIONS …

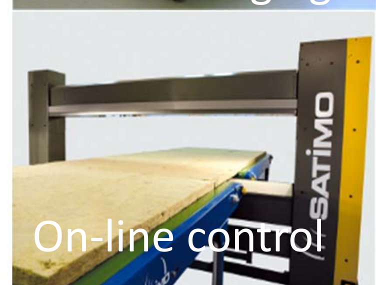


- EARLY 80's… "MICROWAVES OFFER PROMISES AS IMAGING MODALITY"
  L.E. Larsen and J.H. Jacobi
  (*Diagnostic Imaging in Clinical Medicine*, ***11***, *44-47,1982)*
- WHAT EXACTLY MICROWAVES ARE PROMISING OF ? AND BY WHEN ? REMAIN OPEN QUESTIONS
- INDEED, ALMOST 40 YEARS LATER, MICROWAVES ARE STILL CLAIMING TO OFFER PROMISES… BUT ONLY GAINED A MODEST CLINICAL ACCEPTANCE
- BY THA 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 QUALTITATIVE 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)



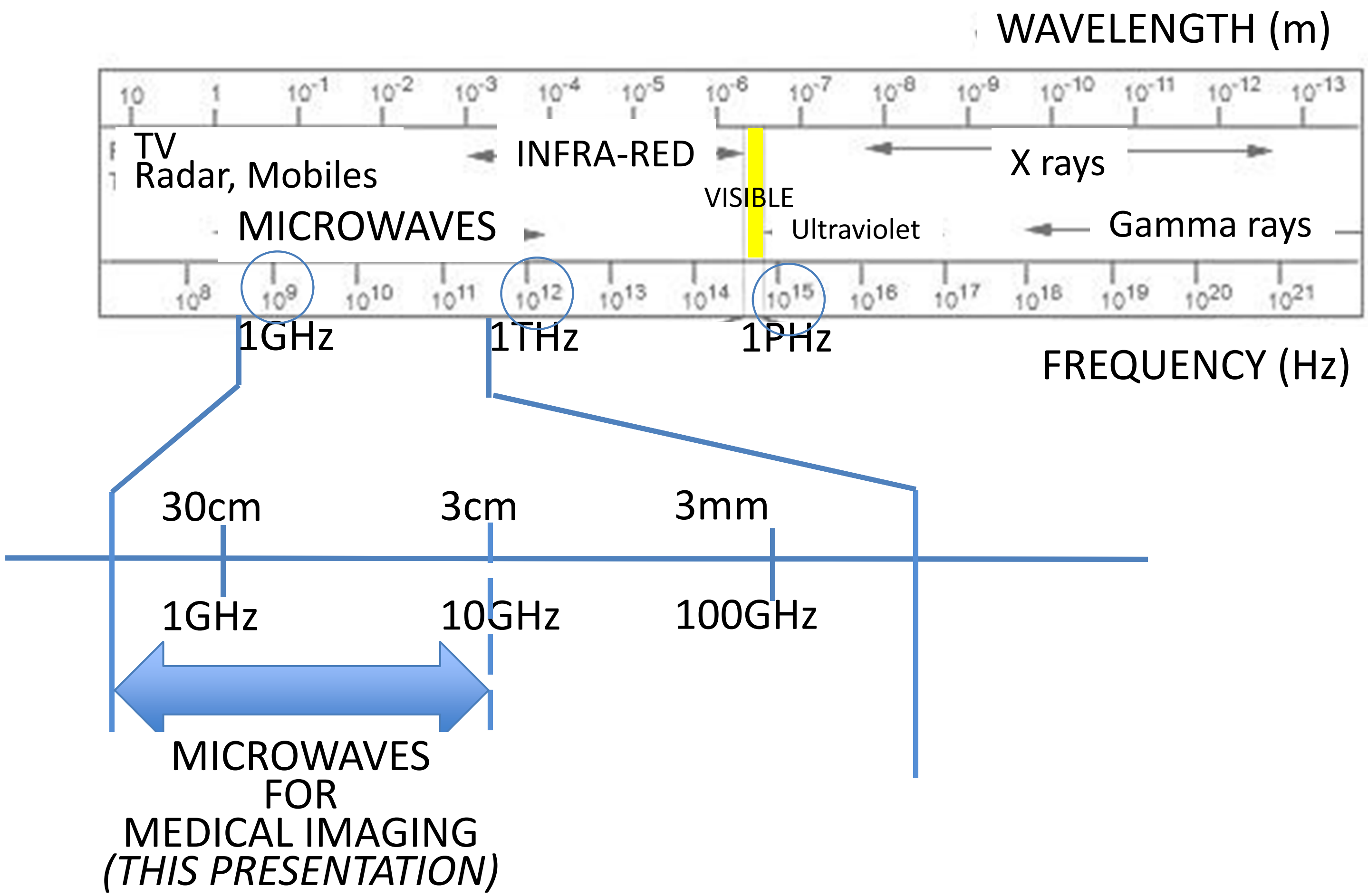


CONTENT

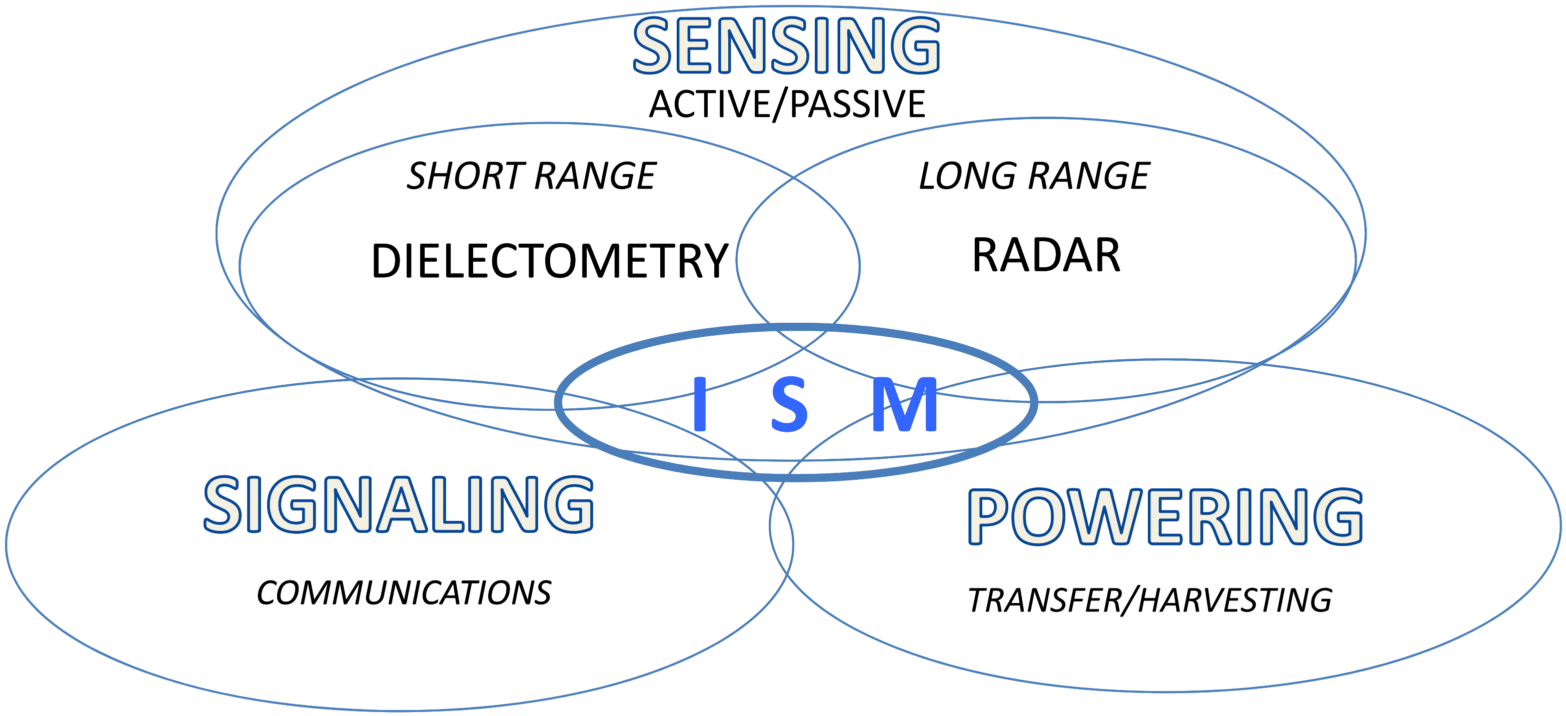
- INTRODUCTION TO MICROWAVES AND MEDICAL IMAGING
- MICROWAVE-BASED IMAGING FOR MEDICAL APPLICATIONS
  - GENESIS
  - FROM PROJECTION TO TOMOGRAPHY
  - FROM MODELS TO PATIENT BED
- A TEST CASE: BREAST IMAGING
- SO, QUALITATIVE OR QUANTITATIVE ?
- SUGGESTIONS AND CONCLUSIONS

MICROWAVES IN THE EM SPECTRUM

(AS A REMINDER)



SIMPLIFIED CLASSIFICATION MAP OF MICROWAVE-BASED APPLICATIONS



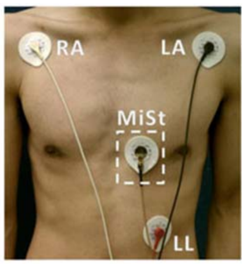
ISM: INDUSTRIAL, SCIENTIFIC, MEDICAL
IS2M: INDUSTRIAL, SCIENTIFIC, SECURITY, MEDICAL

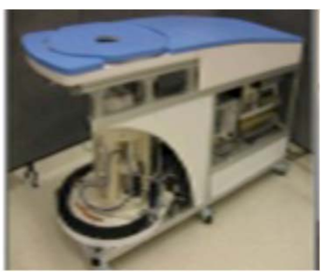
VARIOUS ASPECTS OF MICROWAVES FOR MEDICAL APPLICATIONS

Industrial
Scientific
Medical

« Low » power

« High » power





DIAGNOSIS

BIO-SENSING

IMAGING

HYPER-THERMIA

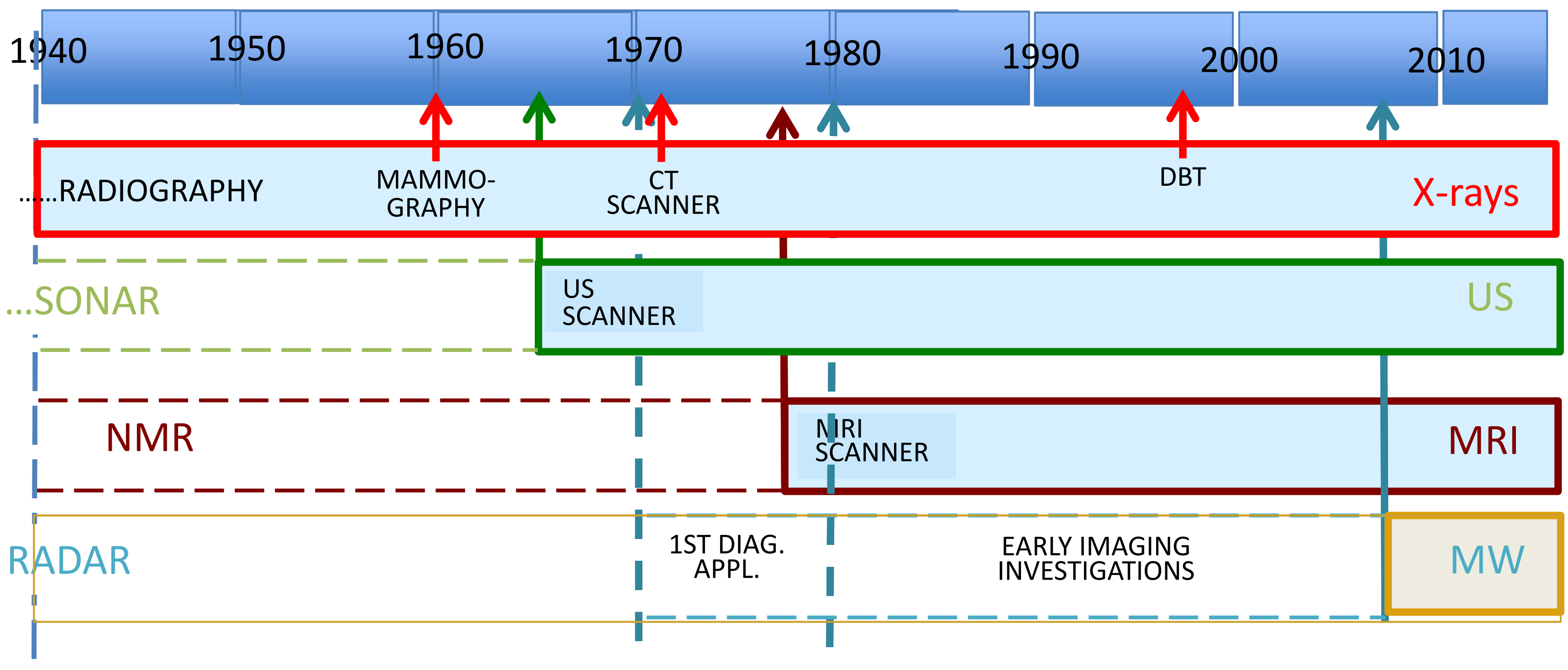
ABLATION

THERAPY

[1] *M.F. Iskander and C.H. Durney, "Electromagnetic Techniques for Medical Diagnosis: a Review", Proc. IEEE, 68, 226-132, Jan. 1980*

[2] *A.W. Guy, "History of Biological Effects and Medical Applications Of Microwave Energy", IEEE Trans. MTT-32, 226-132,Sept. 1984*

TIME LINE OF MAJOR IMAGING MODALITIES MICROWAVES AS THE "LAST COMER"

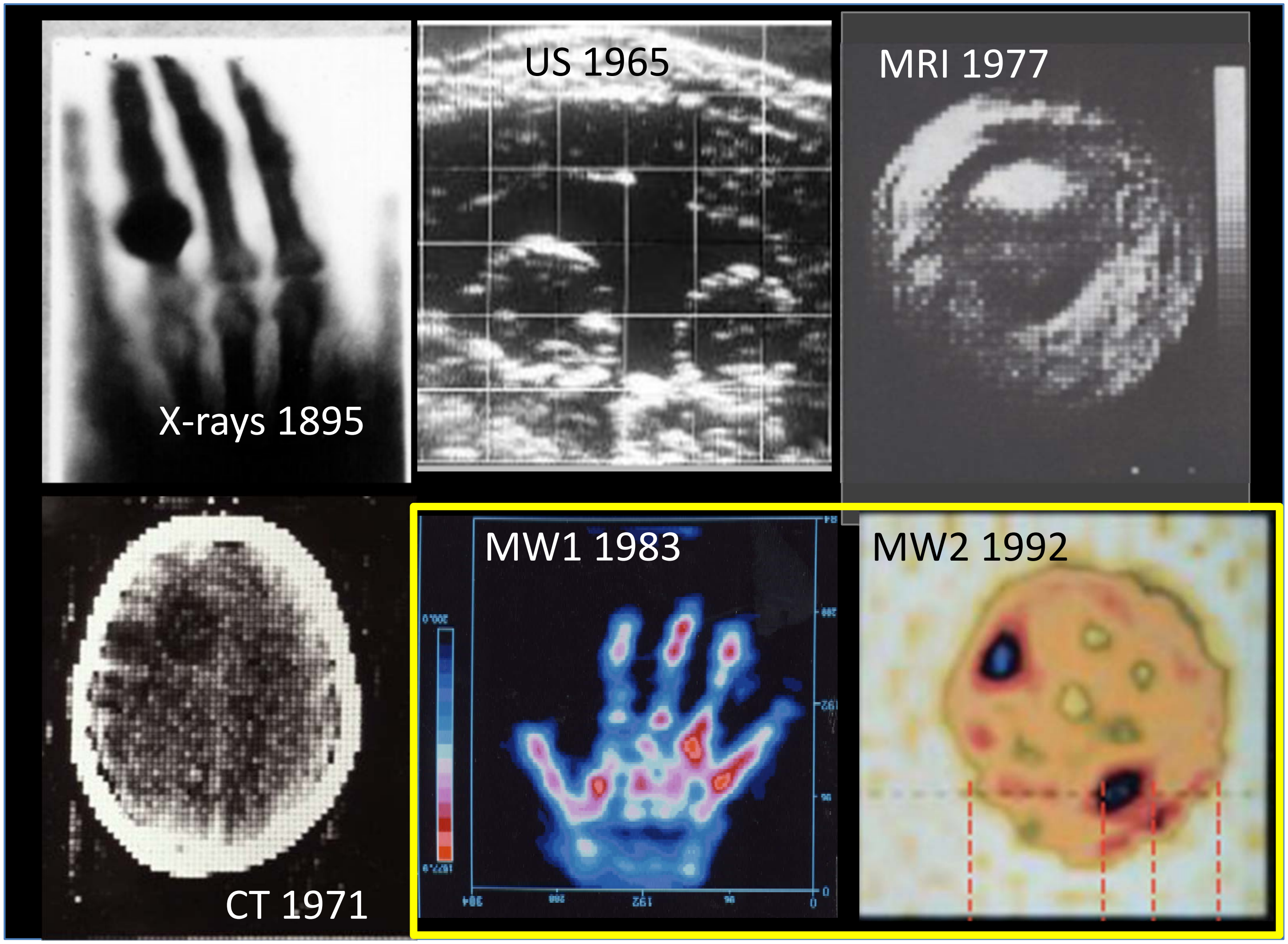


[1] R. Ciernak, "X-Ray Computed Tomography in Biomedical Engineering", Springer-Verlag London Limited, 2011

[2] J. Woo, "A short history of the Real-time ultrasound scanner", http://www.ob-ultrasound.net/history-realtime.html

[3] T. Geva, "Magnetic Resonance Imaging: Historical Perspective", Journ. Cardiovascular Magnetic Resonance, 8, 573-580, 2006

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

Modality	Ultrasound	X-ray	CT	MRI	MW
What is imaged	Mechanical properties	Mean tissue absorption	Tissue absorption	Biochemistr (T₁ and T	Dielectric permittivity
Access	Small windows adequate	2 sides needed	Circumferential Around body	Circumferer Around b	Planar Around body
Spatial resolution	Frequency and axially dependent 0.3–3 mm	~1 mm	~1 mm	~1 mm	Frequency and tissue dependent
Penetration	Frequency dependent 3–25 cm	Excellent	Excellent	Excellent	Frequency and tissue dependent
Safety	Very good	Ionizing radiation	Ionizing radiation	Very good	Very good
Speed	100 frames/sec	Minutes	½ minute to minutes	10 frames/se	System dependent
Cost	$	$	$$$$	$$$$$$$$	$$??
Portability	Excellent	Good	Poor	Poor	Good

From J. Berkoff, "Ultrafast Ultrasound Imaging", Intechopen, ISBN 978-953-307-279-1, 2011

DIELECTRIC PROPERTIES OF LIVING TISSUES
(IN SHORT…)

- 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 λ cm (spatial resolution #λ/2)

dielectric constant — conductivity

$$\varepsilon_c = \varepsilon'_r - j\,\sigma(\omega)$$

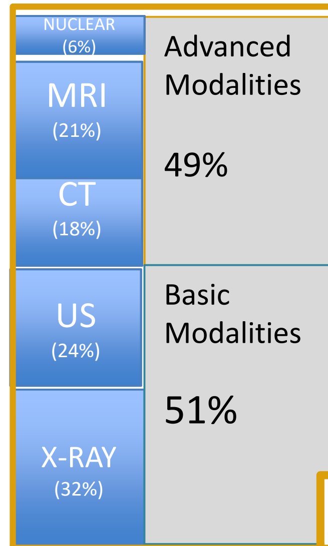
$\omega = 2\pi f$

		MUSCLE (high water content)				LUNG (medium water content)				BONE (low water content)			
F GHZ	λ_0 cm	ε'_r	σ s/m	L cm	λ cm	ε'_r	σ s/m	L CM	λ cm	ε'_r	σ s/m	L CM	λ cm
0.433	69.3	53	1.43	3	8.5	36	0.72	4.7	10.8	5.6	0.08	16.3	28.2
0.915	33.8	51	1.60	2.5	4.4	35	0.73	4.5	5.4	5.6	0.10	12.8	13.7
2.450	12.3	49	2.21	1.7	1.8	32	1.32	2.3	2.2	5.5	0.16	7.9	5.2
5.800	5.2	43	4.73	0.8	0.8	28	4.07	0.7	1.0	5.1	0.26	4.7	2.3
10.00	3.0	40	10.3	0.3	0.5	25	9.08	0.3	0.6	4.5	0.44	2.5	1.4

A GLOBAL VIEW ON MEDICAL IMAGING
A MARKET VIEWPOINT

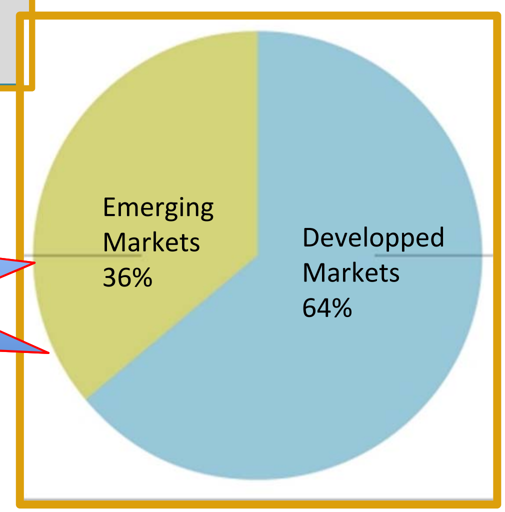
- SALIENT MARKET FEATURES:
  - Market growth supported by the rise of geriatric population and the increased prevalence of CV diseases,
  - Expected Growth Rate: 5.4%, to reach US 35 billions end 2019,
  - X-ray first; fastest growth expected for CT and PET (earlier disease detection),
  - Larger growth 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 … ✓

MICROWAVES AS GOOD CANDIDATE ?



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

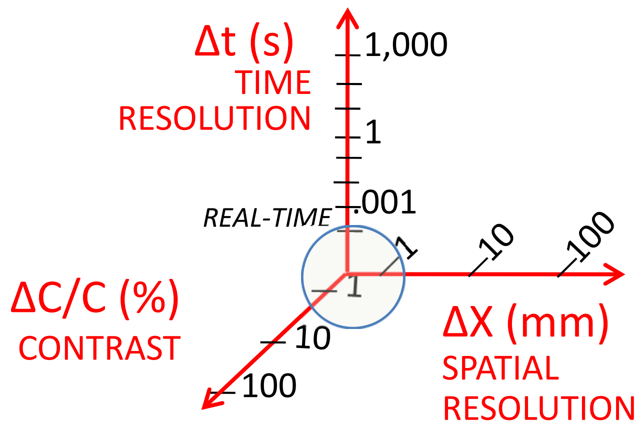
GLOBAL MEDICAL IMAGING MARKET
(From: *Pictures of the Future, Medical Imaging:Facts and Forecasts, siemens.com*)



WHAT CLINICAL ACCEPTANCE IS MADE OF ?
IMAGE QUALITY… BUT NOT ONLY !

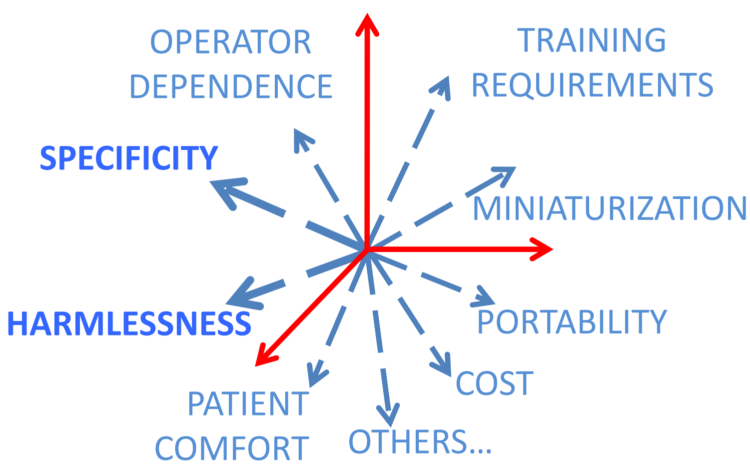
- THE CLINICAL RELEVANCE OF AN IMAGE:
  - DEPENDS ON THE 3-D RESOLUTION PERFORMANCES OF THE IMAGING SYSTEM
  - USUALLY RESULTS FROM AN APPLICATION-DEPENDENT MIX OF ALL ABOVE ISSUES

3-D RESOLUTION SPACE



- 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

MULTI-D ACCEPTANCE SPACE



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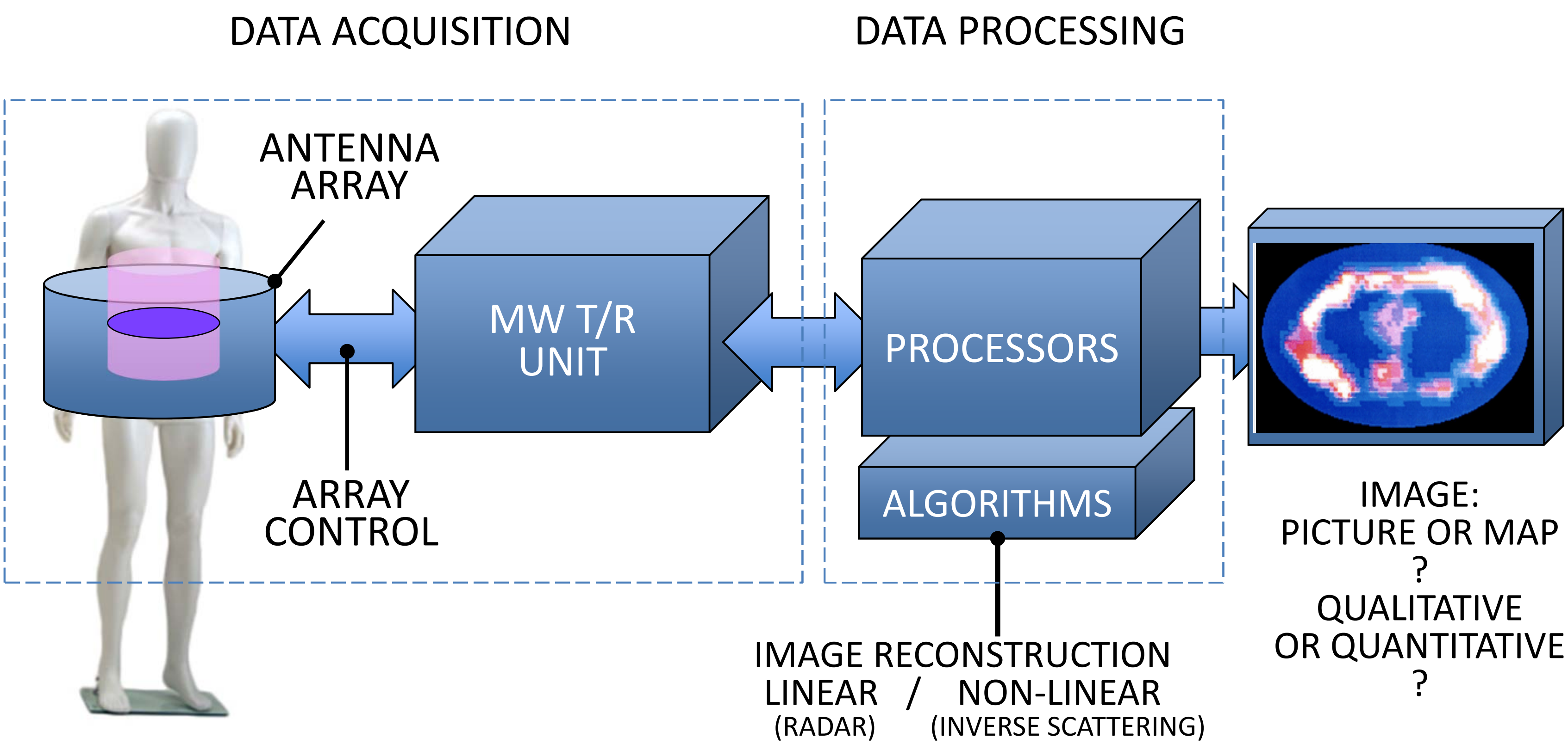
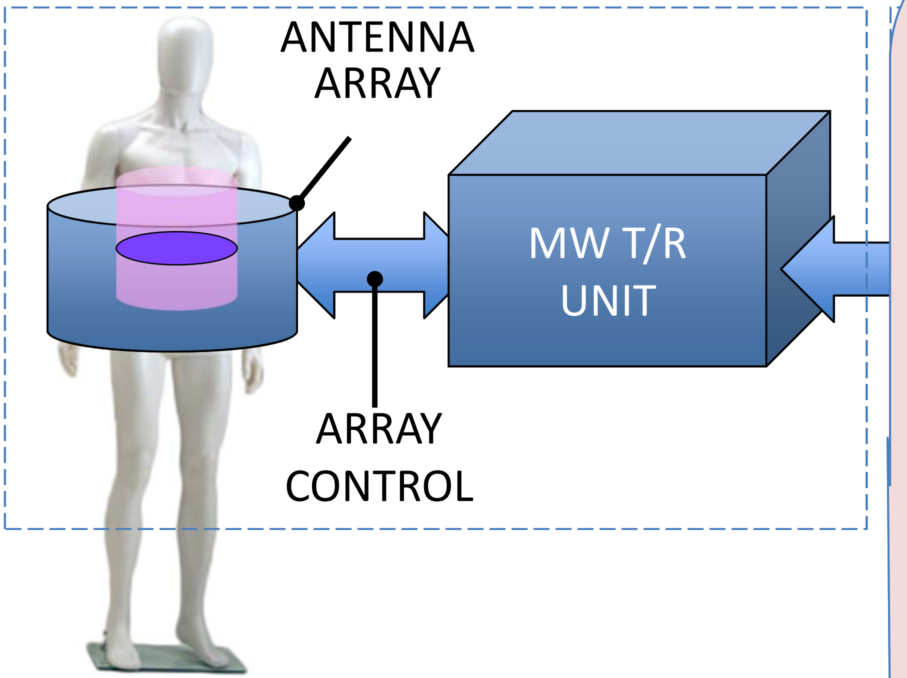
ARCHITECTURE OF GENERIC MW SCANNERS FOR MEDICAL APPLICATIONS (1)



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/parallell addressing
- etc…

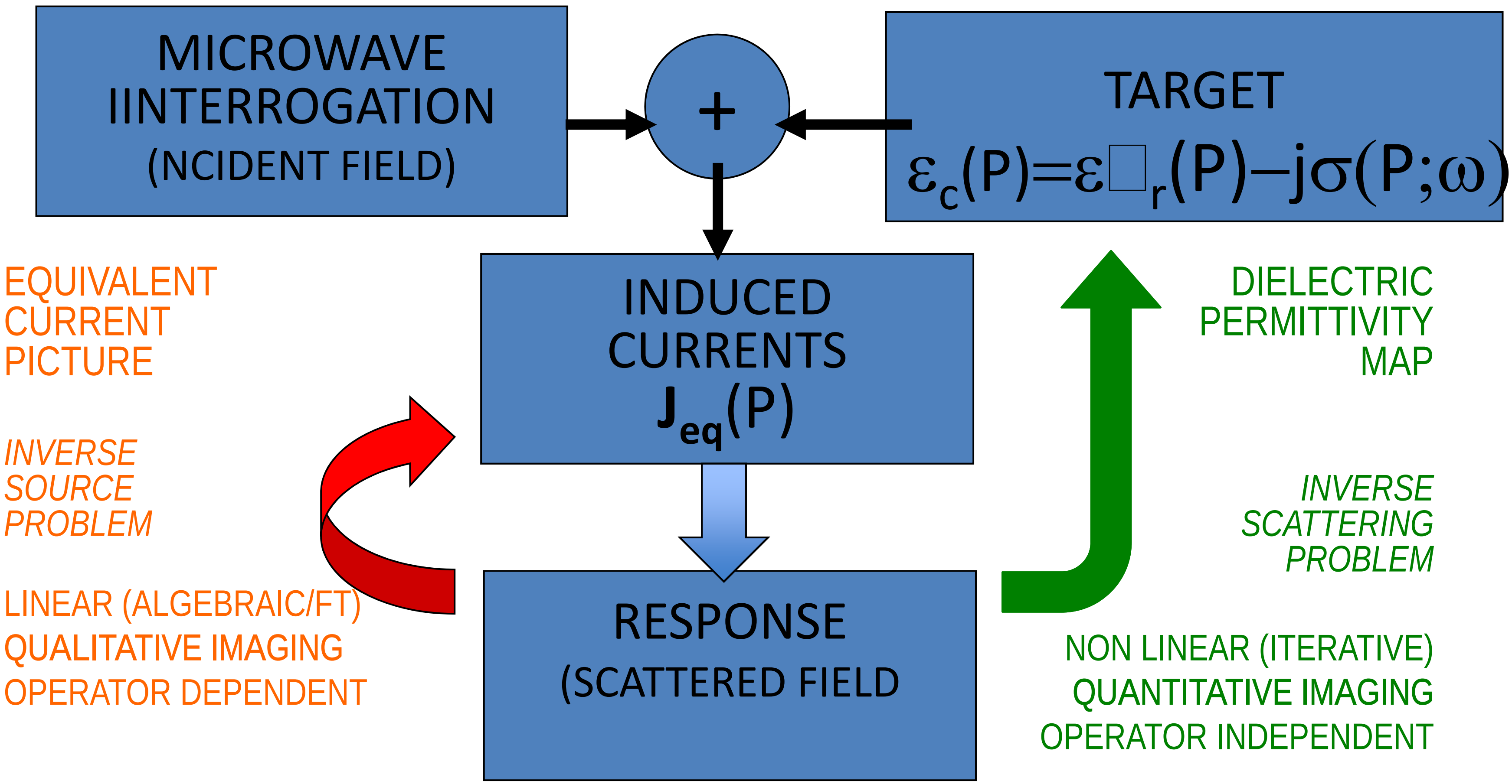
3. Antenna element:
- Mono/dipole, slots patch, vivaldi, dielectric filled waveguides, cavity backed, etc…
- Single/dual polarization
- Contact / Contactless / Shielded
- etc…

R. Chandra, H. Zhou, I. Balasingham, R.M. Narayanan, *"On the opportunities and challenges in microwave medical sensing and imaging"*, IEEE Trans. Biomed. Eng. 62, 1667–1681 (2015)

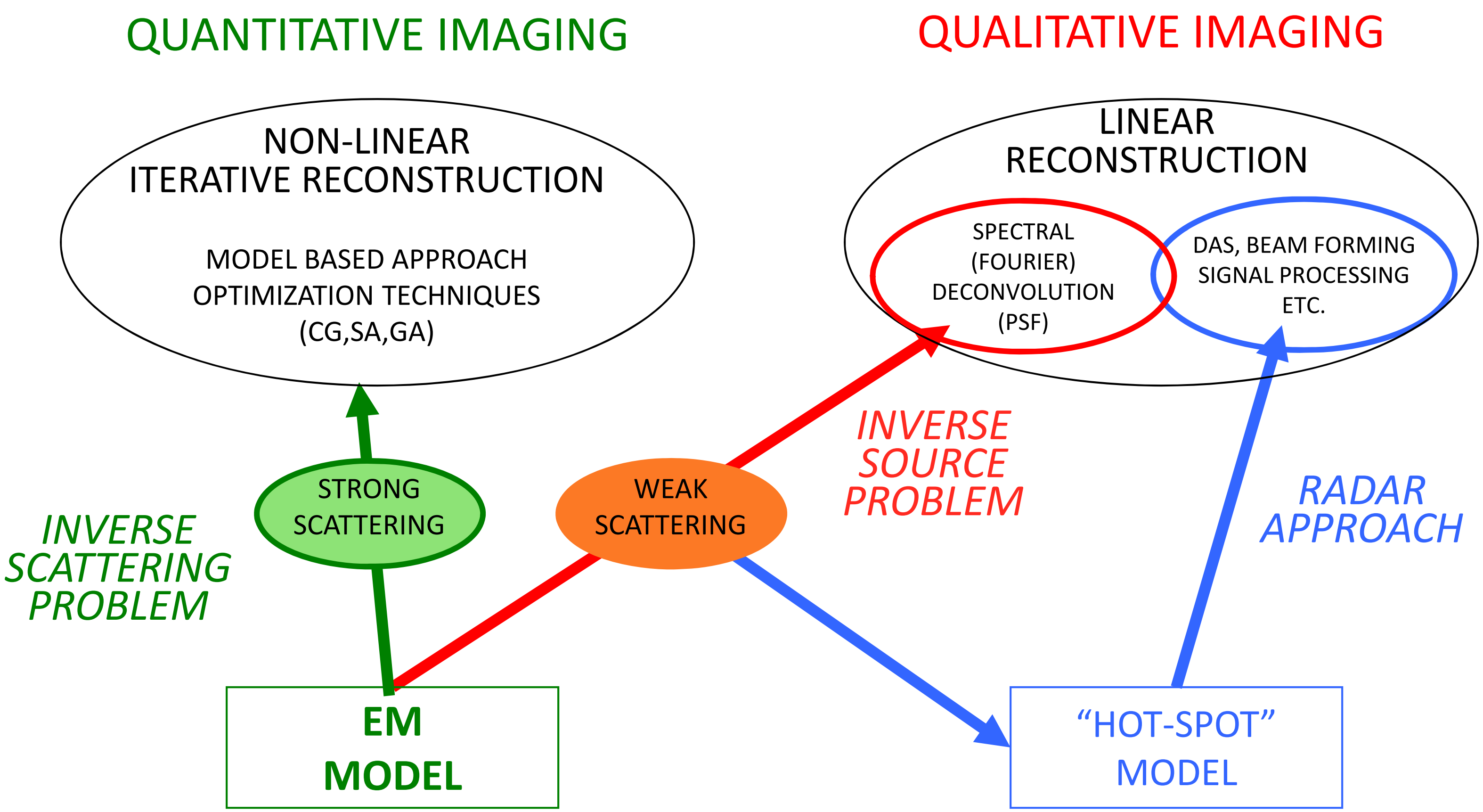
Berenice Borja1, Jose A. Tirado, Hildeberto Jardon,"*An Overview of UWB Antennas for Microwave Imaging Systems for Cancer Detection Purposes" Progress In Electromagnetics Research B*, Vol. 80, 173–198 (2018)

PRINCIPLE OF IMAGE RECONSTRUCTION FOR MICROWAVE-BASED MEDICAL APPLICATIONS

QUALITATIVE AND QUANTITATIVE APPROACHES TO INVERSE SCATTERING PROBLEMS

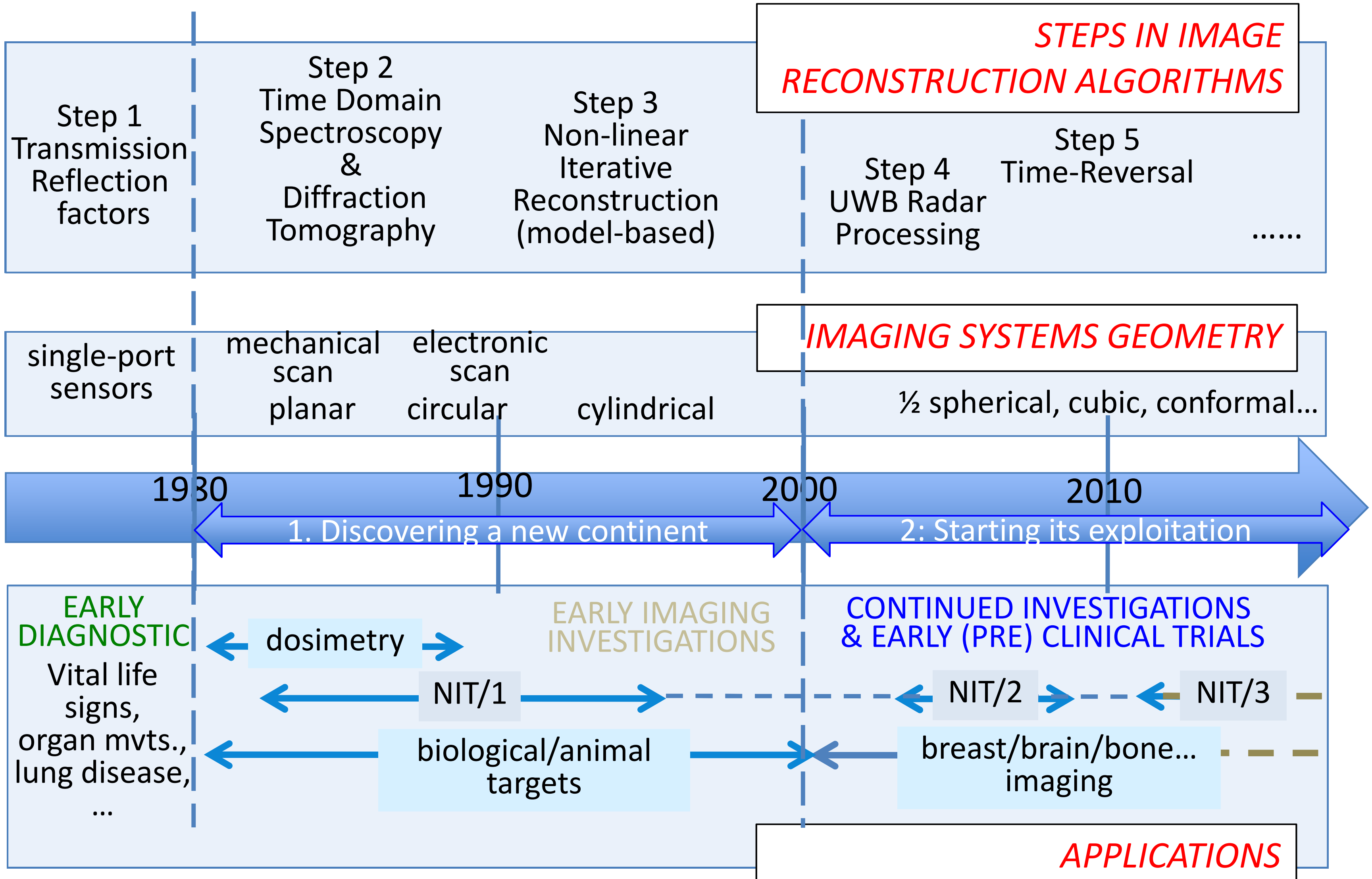


SIMPLIFIED FAMILY TREE OF RECONSTRUCTION ALGORITHMS

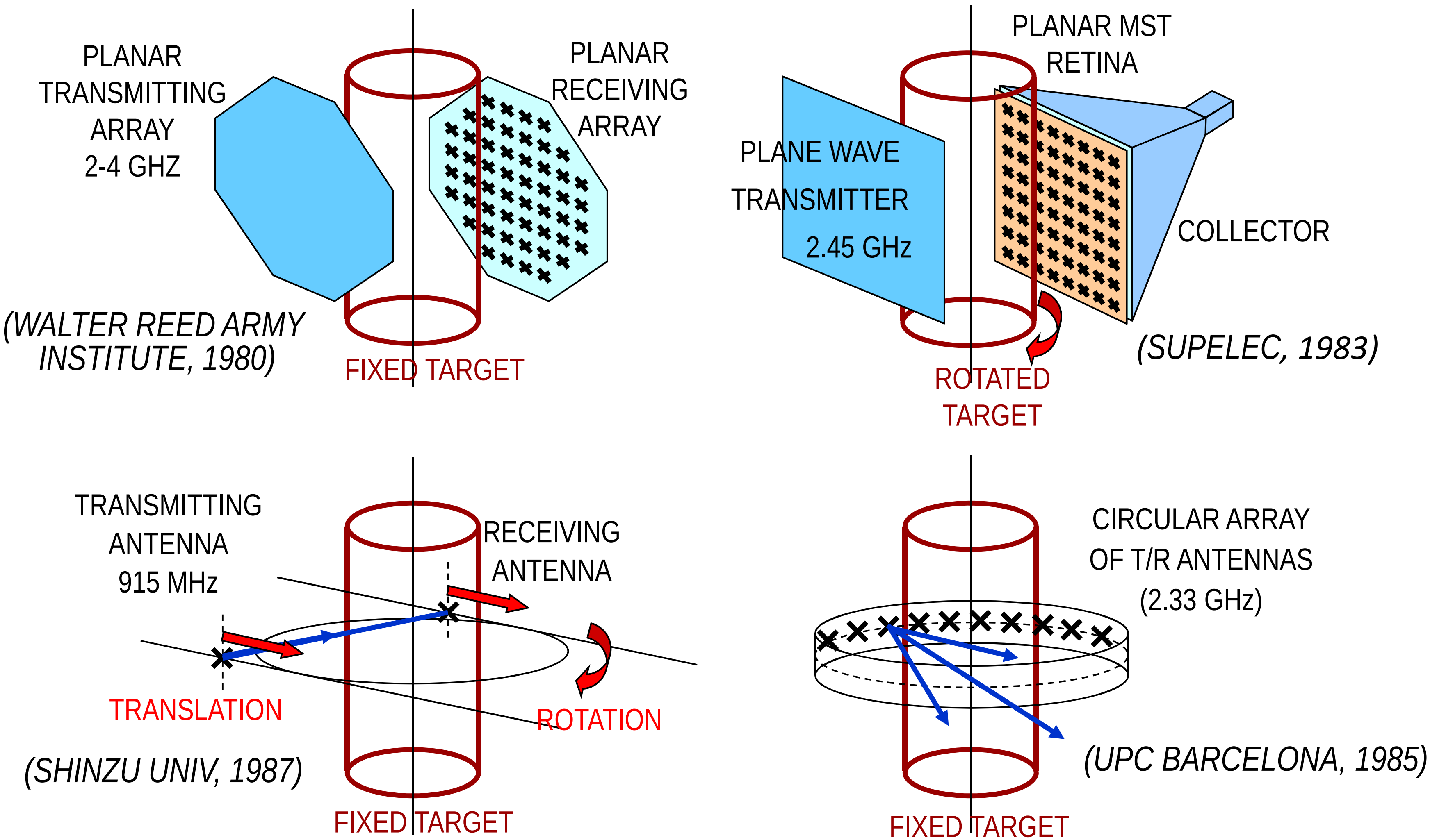


MW FOR MEDICAL DIAGNOSTIC APPLICATIONS

SIGNIFICANT MILESTONES

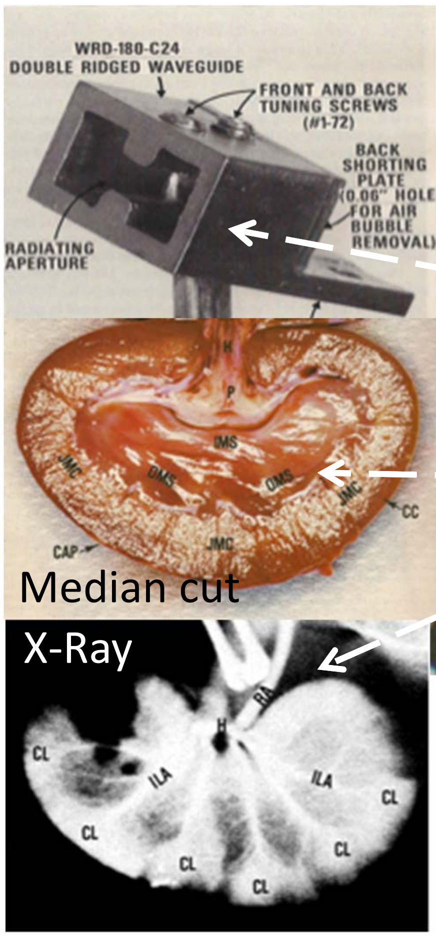


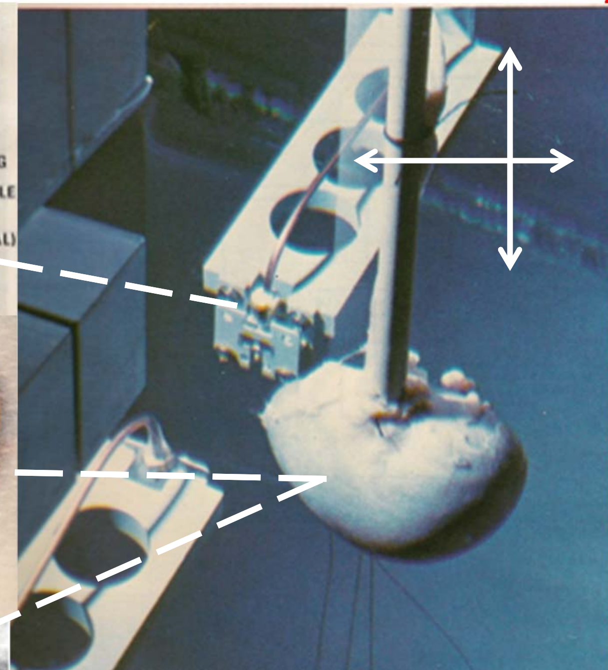
EXAMPLES OF EARLY ARRANGEMENTS FOR MICROWAVE TOMOGRAPHY



FIRST MICROWAVE IMAGES OF PERFUSED ORGANS (1)

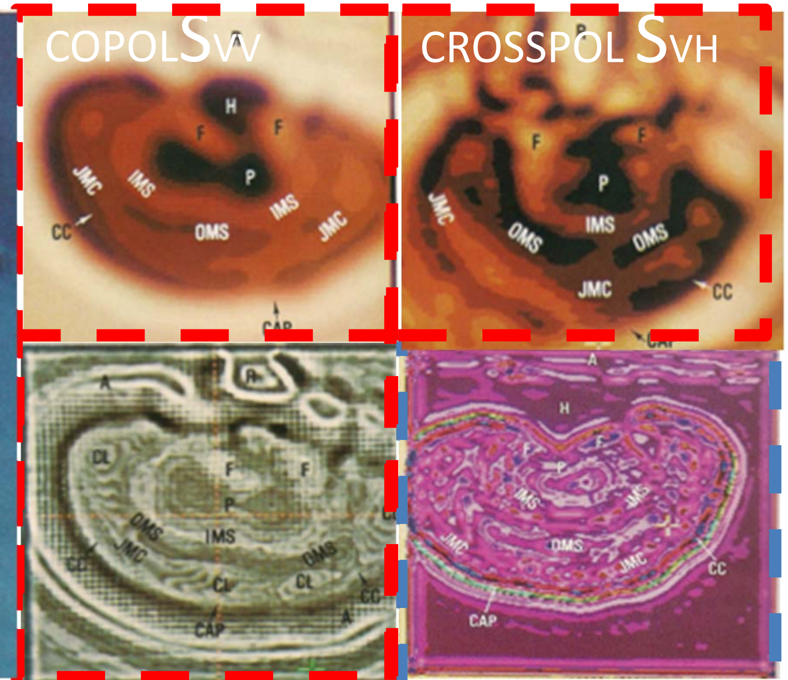
RASTER SCAN TRANSMISSION IMAGING (WRAI, 1979)





MECHANICAL RASTER SCAN:

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



CW: 3.9 GHz (1)
CO&CROSS-POL

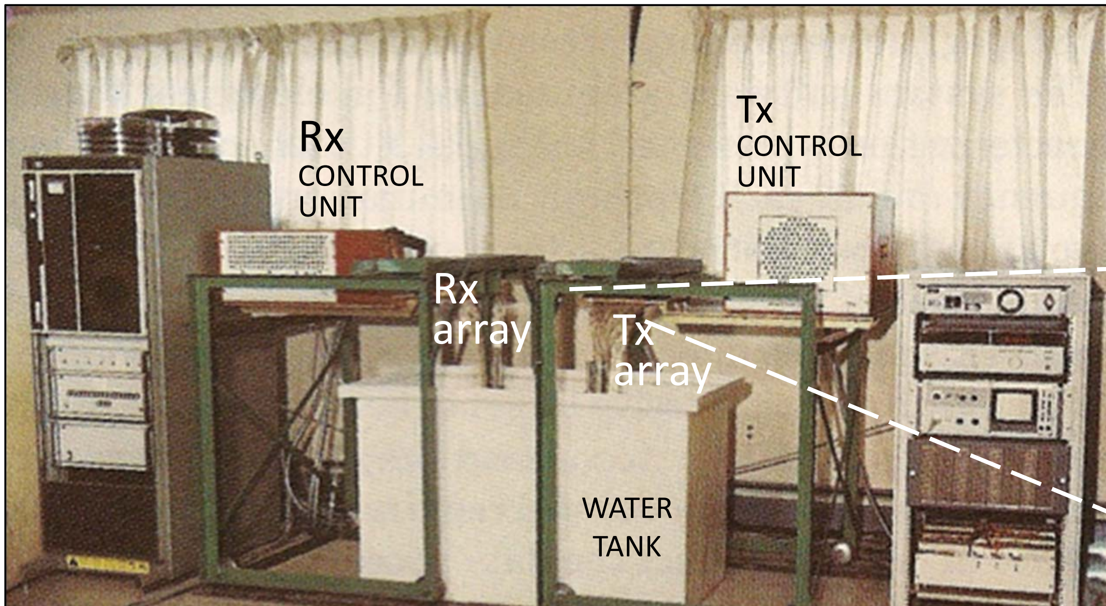
LINEAR FM (2):
2 – 4 GHz, UWB
(MW-TDS)

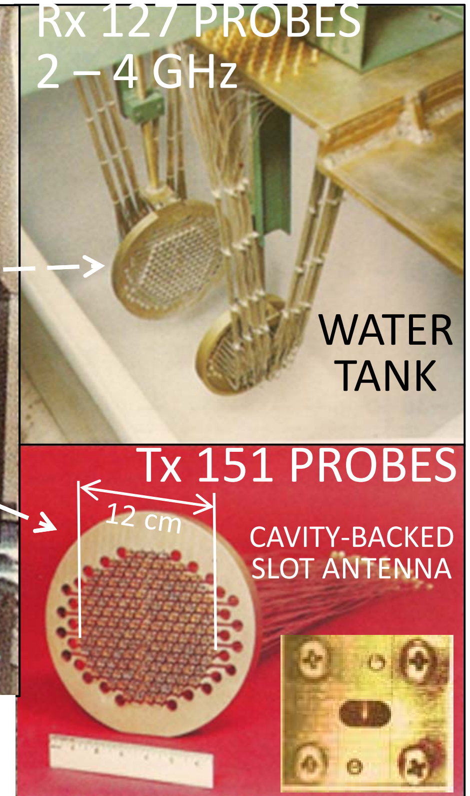
MICROWAVE IMAGES

DETAILED INTERPRETATION IN TERMS OF CANINE RENAL ANATOMY AND PHYSIOLOGY

1. *(L.E. Larsen and J.H. Jacobi," Microwave Scattering Parameter Imaging of an Isolated Canine Kidney", Medical Physics, Vol. 6, pp. 394-403, 1979)*
2. *(J.H. Jacobi and L.E. Larsen," Linear FM Pulse Compression Radar Techniques Applied to Biological Imaging", In Medical Applications of Microwave Imaging, pp. 138-147, IEEE Press, 1986)*

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.

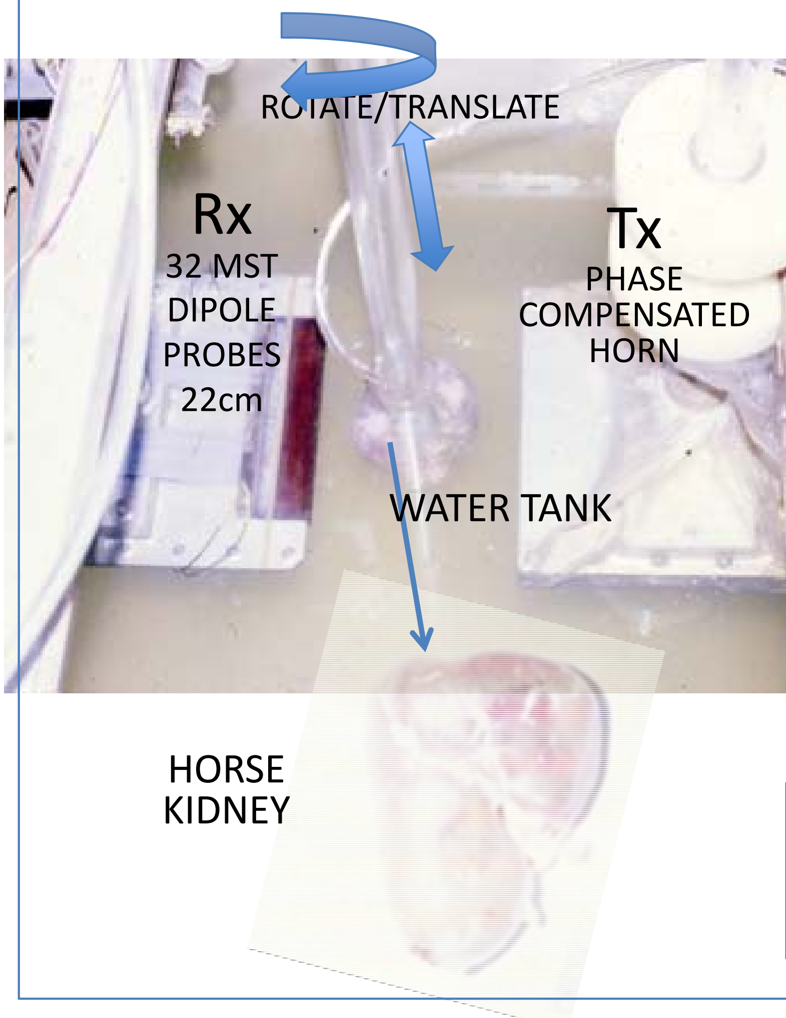
(S.J. Foti et al.,“ A Water-Immersed Microwave Phased Array System for Interrogation of Biological Targets”, In Medical Applications of Microwave Imaging, IEEE Press, 1986)

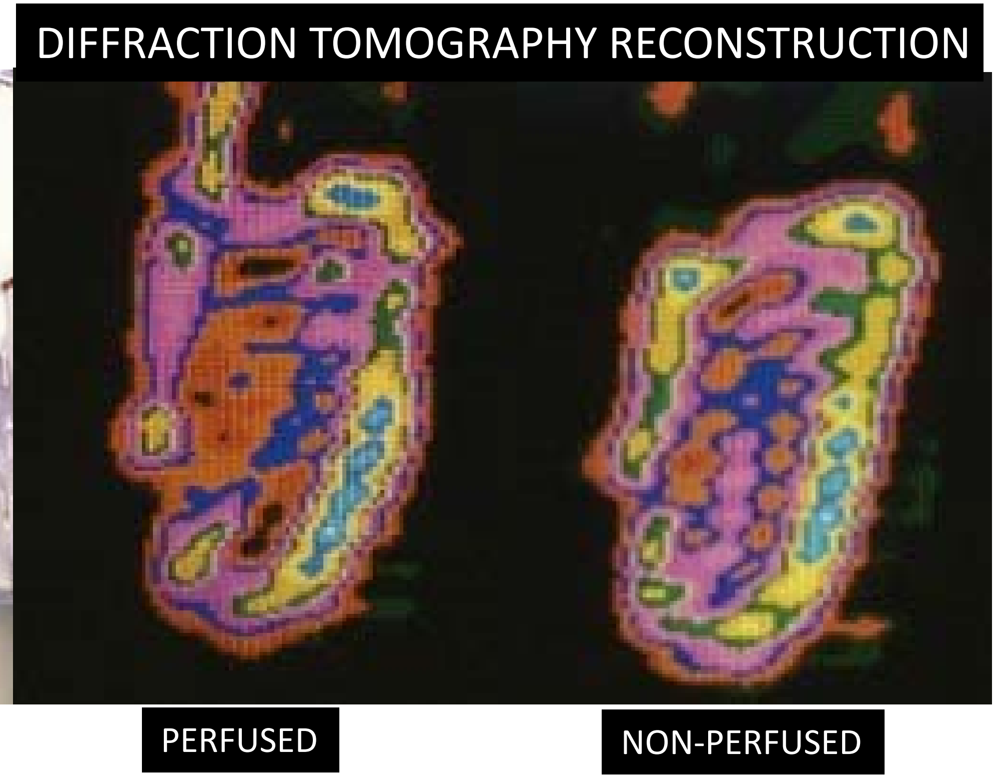
A PERSISTING MYSTERY:
NO PUBLISH RESULT !

FIRST REAL-TIME HUMAN IMAGES (1)

MW TOMOGRAPHY OF BIOLOGICAL TARGETS (SUPELEC, 1982-2000)

LINEAR MODULATED SCATTERING TECHNIQUE PROBE ARRAY

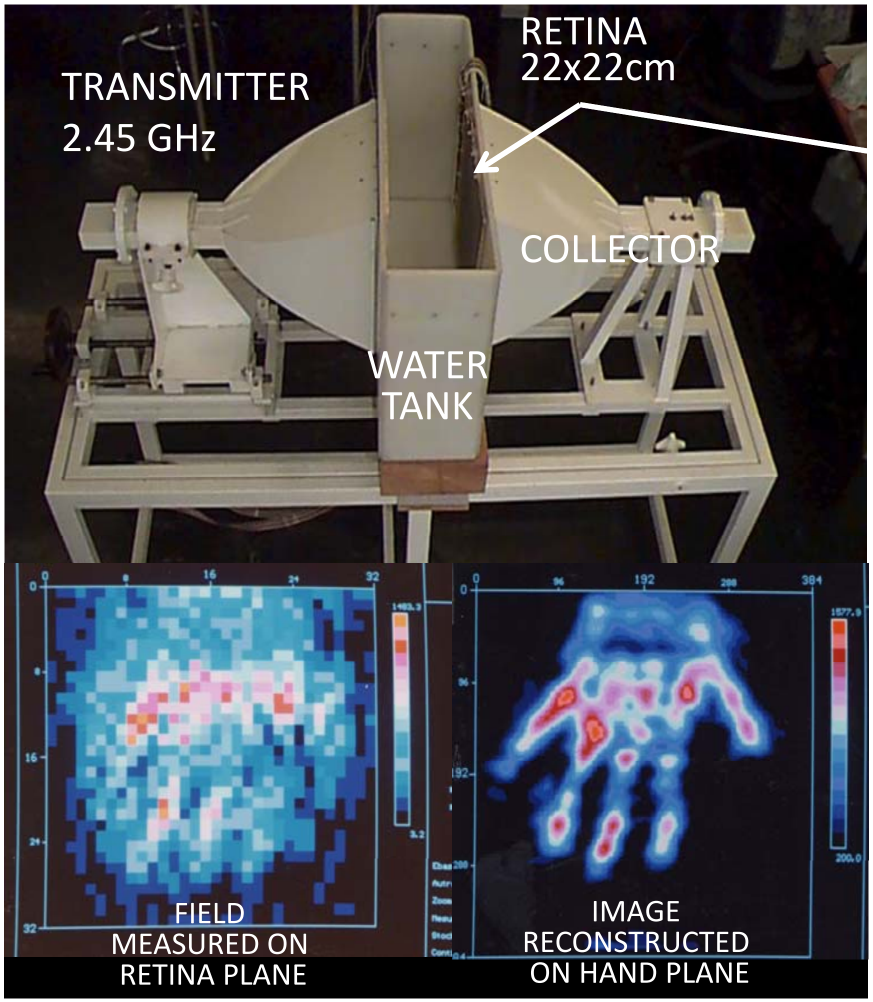


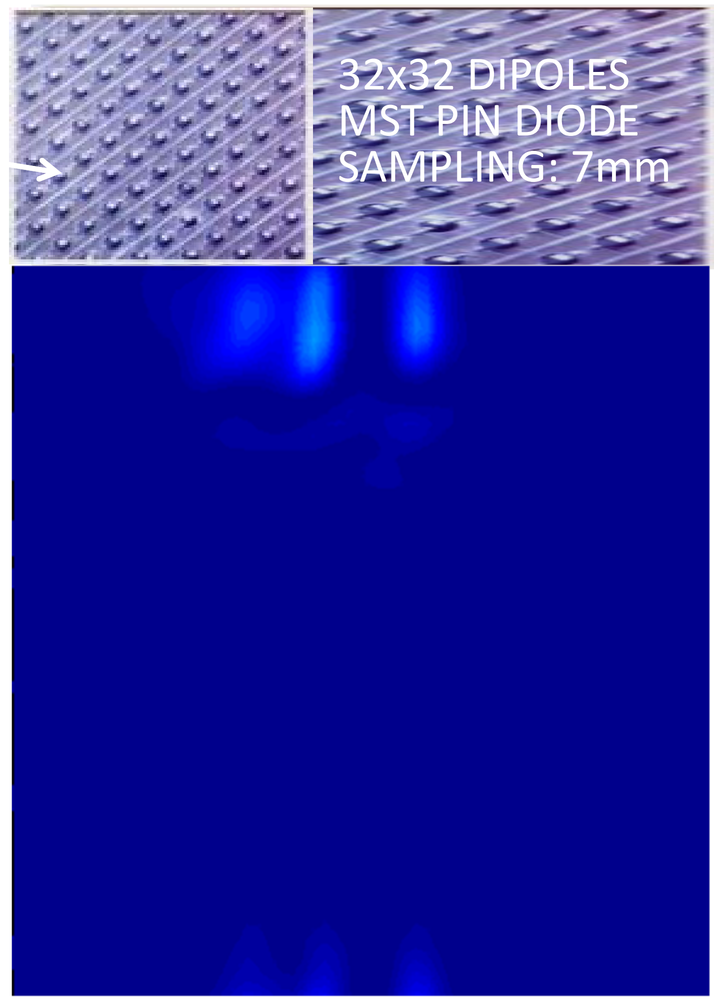


J.Ch. Bolomey, A. Izadnagahdar, L. Jofre, C. Pichot, G. Peronnet, M. Soleimani, "Microwave Diffraction Tomography For Biomedical Applications", MTT-S IEEE Trans., Nov. 1982)

C. Pichot, L. Jofre, G. Peronnet, J.C. Bolomey, Active microwave imaging of inhomogeneous bodies. IEEE Trans. Antennas Propag. 33, 416–425 (1985)

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

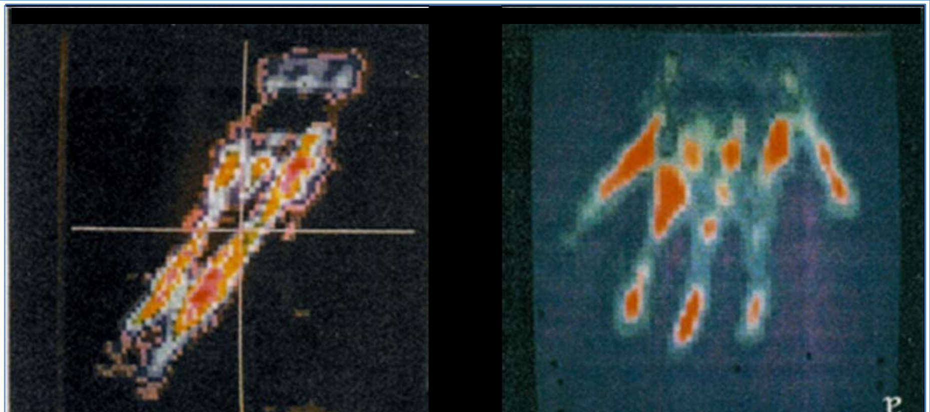




(A. Joisel and J.Ch. Bolomey, "Rapid Microwave Imaging of Living Tissues" Proc. SPIE's Int. Symp. Medical Imaging, Feb. 2000)

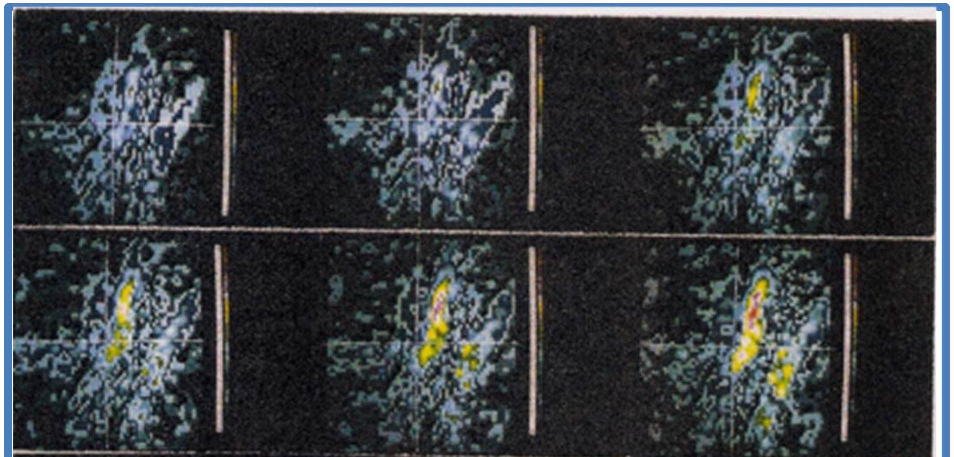
FIRST MICROWAVE IMAGES SENSITIVE TO BLOOD FLOW RATE AND TEMPERATURE

IN VIVO IMAGERY (FOREARM, HAND)



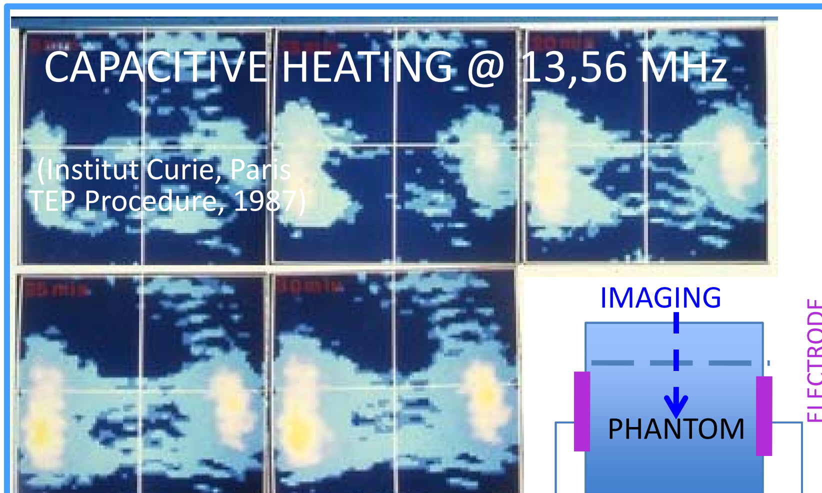
(Laboratoire de Thermobiologie, Strasbourg, TEP Procedure, 1987)

MW IMAGE SENSITIVITY TO BLOOD FLOW RATE

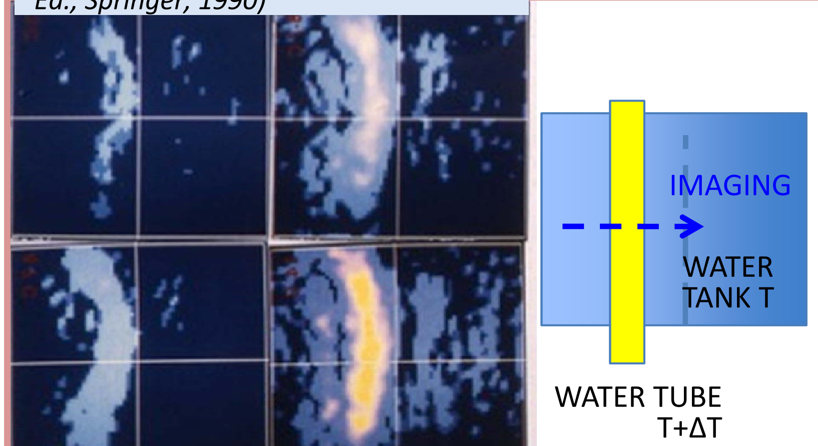


(M.S. Hawley, A. Broquetas, L. Jofre, J.Ch. Bolomey and G. Gaboriaud, "Microwave imaging of tissue blood content changes," Journ. Biomed. Eng., vol.13, May 1991)

MW IMAGE SENSITIVITY TO TEMPERATURE

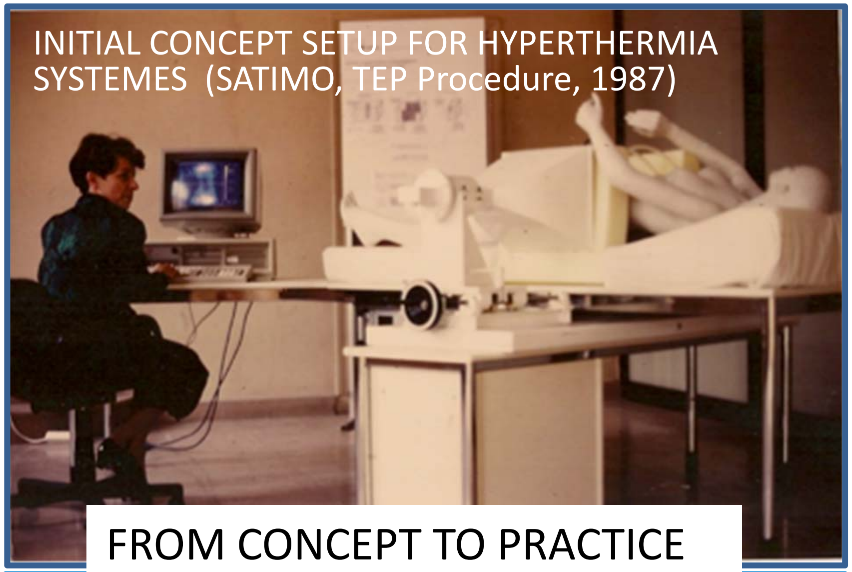


(J.Ch. Bolomey and M.S. Hawley, in Clinical Thermology, Methods of Hyperthermia Control, M. Gautherie Ed., Springer, 1990)



(J.Ch. Bolomey, L. Jofre, G. Peronnet, « On the possible use of microwave Imaging for remote thermal sening », IEEE MTT-Trans., 31,9, Sept. 1983)

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



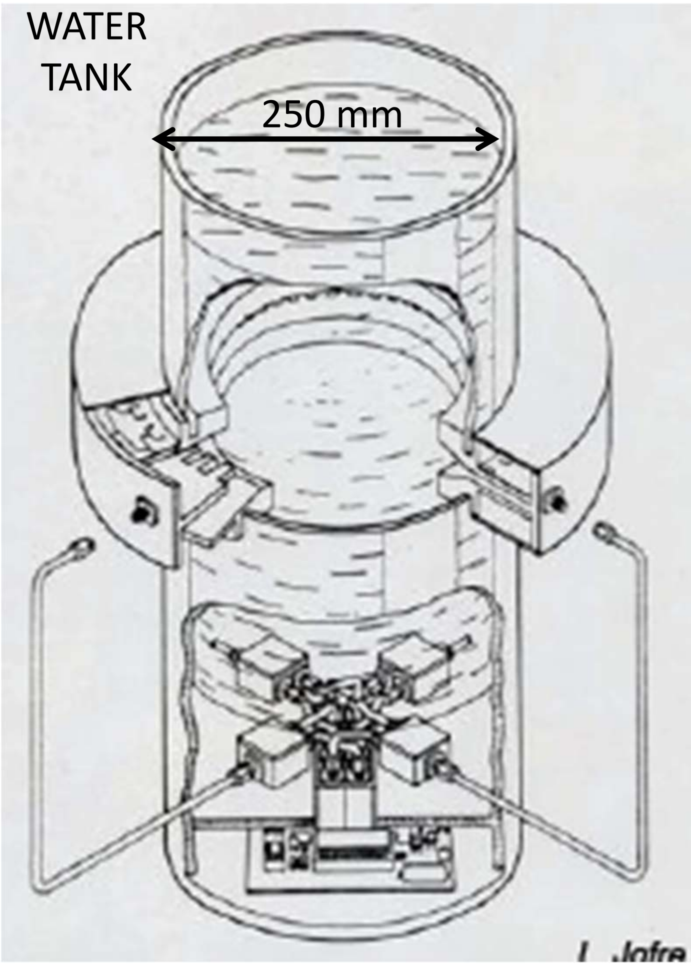
FROM CONCEPT TO PRACTICE

- 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):
  - SUCCESFULL 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

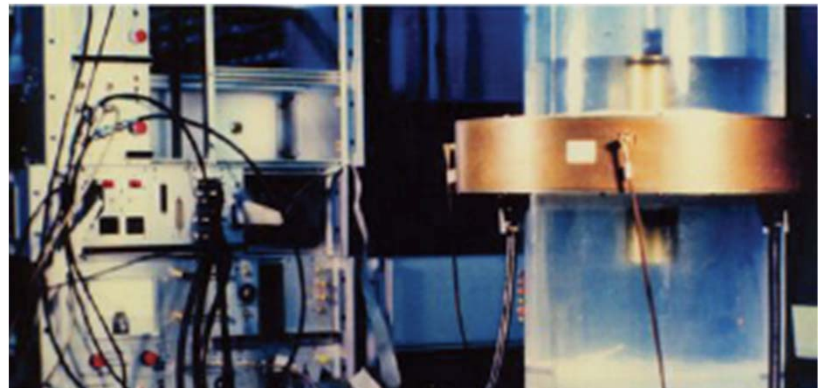
* BUT, AN EVIDENT LACK OF COMPUTING POWER !

THE FIRST MICROWAVE SCANNER
UPC BARCELONA, 1990

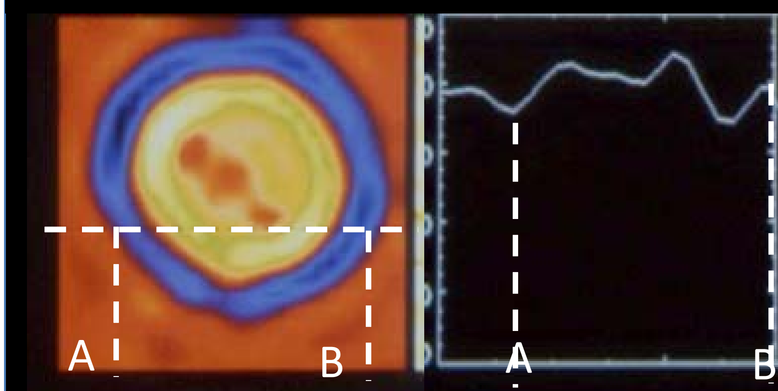


CIRCULAR
ARRAY
64 Tx/Rx
ANTENNAS
(water filled)

FREQUENCY
2.3 GHz



LINEAR RECONSTRUCTION
(DIFFRACTION TOMOGRAPHY)
32 VIEWS; 32 DATA/VIEW
HUMAN FOREARM

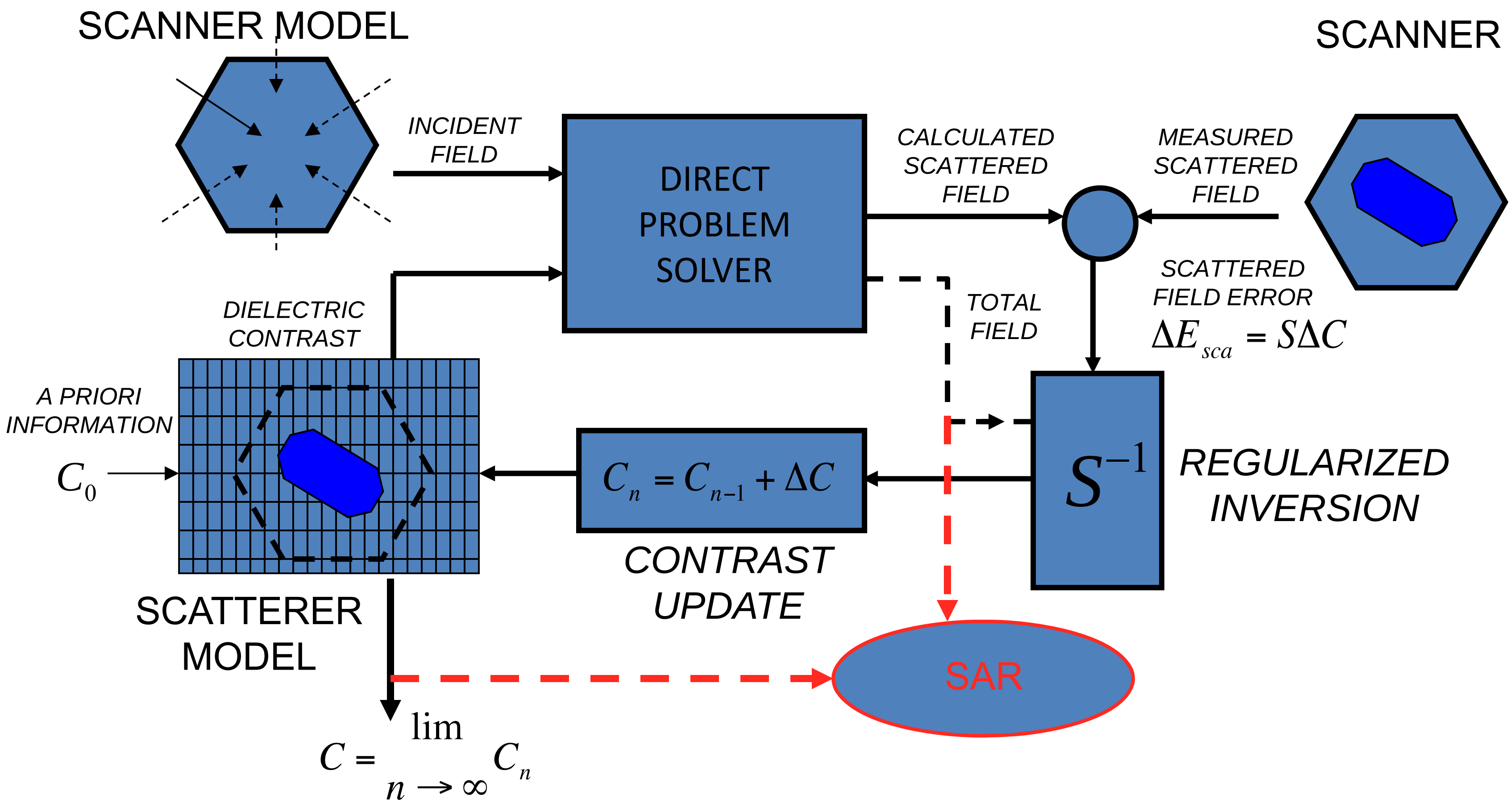


1. *L. Jofre et al., "Medical Imaging with a Microwave Scanner," IEEE Trans. on Biomedical Engineering, Vol. 37, 303-312,March 1990.*
2. *A. Broquetas et al., "Cylindrical Geometry: A Further Step in Active Microwave Tomography," IEEE Trans. Microwave Theory and Techniques,, May 1991.*

INVERSE PROBLEM AS A SEQUENCE OF DIRECT PROBLEMS

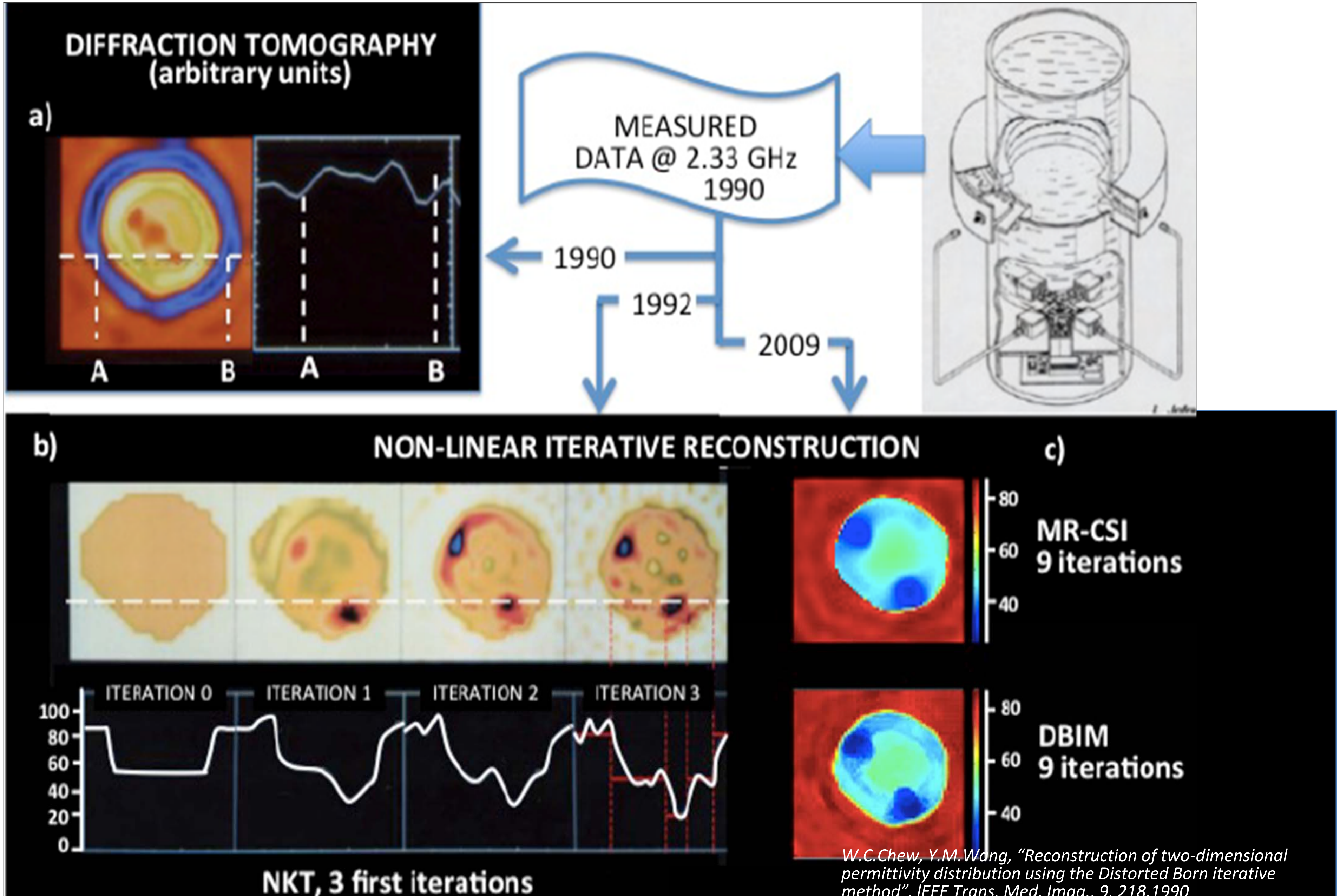
APPLICATION TO ITERATIVE TOMOGRAPHIC RECONSTRUCTION

(AND SAR MEASUREMENT)



* N. Joachimowicz et al. "Inverse Scattering: An Iterative Numerical Method for Electromagnetic Imaging" IEEE Trans.AP, Vol-39, No. 12, pp. 1742–1752, December 1991.

* W. C. Chew and Y. M. Wang, "Reconstruction of Two-Dimensional Permittivity Distribution Using the Distorted Born Iterative Method", IEEE Transactions on Medical Imaging, Vol-9, No. 2, pp. 218-225, April 2004.



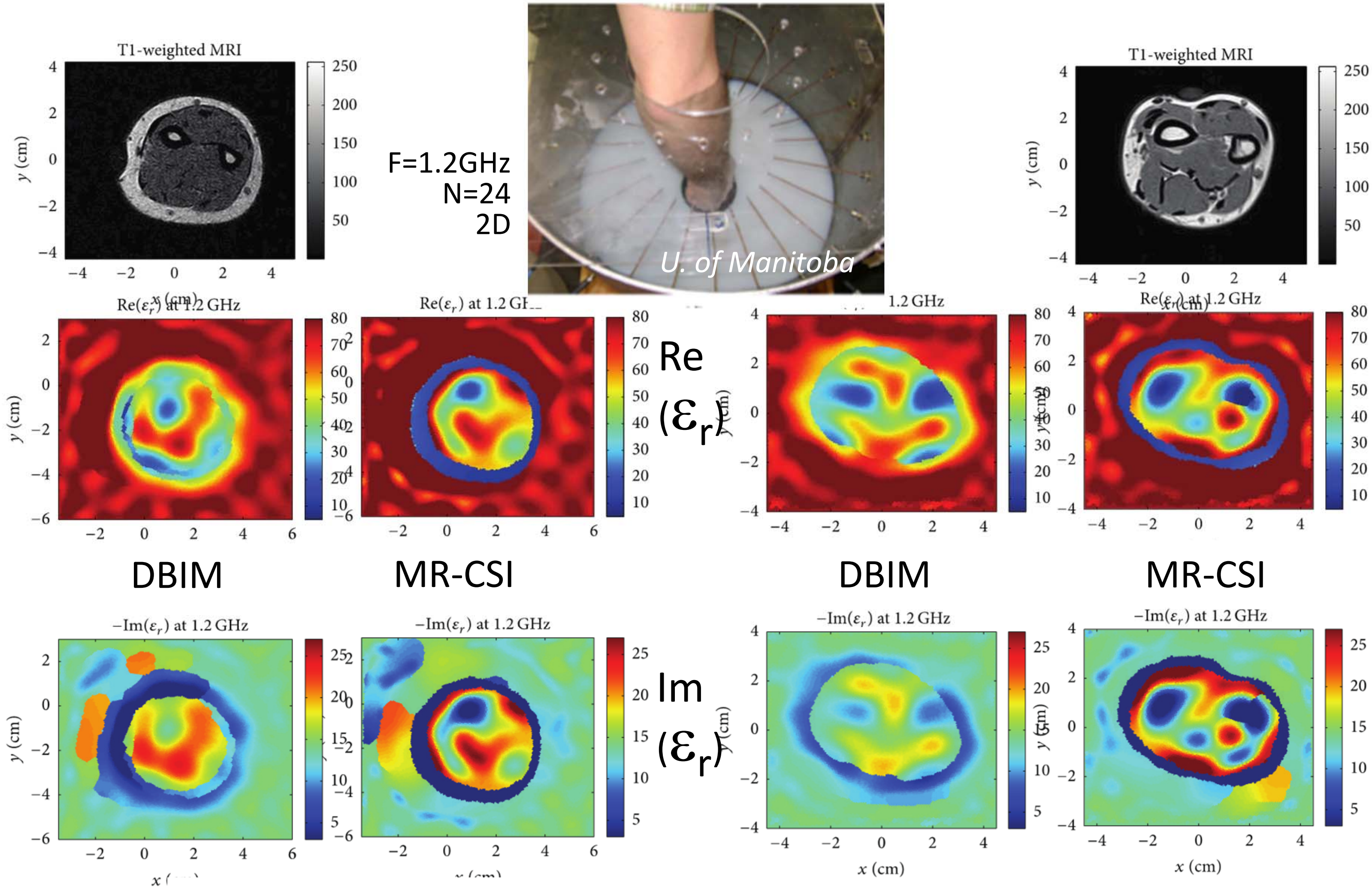
W.C.Chew, Y.M.Wang, "Reconstruction of two-dimensional permittivity distribution using the Distorted Born iterative method", IEEE Trans. Med. Imag., 9, 218,1990

N. Joachimowicz, Ch. Pichot and J.P. Hugonin., "Inverse Scattering: an Iterative Numerical Method for Electromagnetic Imaging", IEEE Trans. AP-39, 1742-1753, December 1991.

C. Gilmore, P. Mojabi and J. Lo Vetri, "Comparison of an Enhanced DBIM Method and the Multiplicative-Regularized Contrast Source Inversion Method" IEEE Transactions on Ant. Prop., Vol-57, No. 8, pp. 2341-2351, August 2009.

LIMB MICROWAVE IMAGING @ 1.2 GHz

EXAMPLE OF PATIENT-TO-PATIENT SENSITIVITY AND ALGORITHM DEPENDENCE



C. Gilmore, E. Zakaria, S. Pistorius and J. Lo Vetri, "Microwave Imaging of Human Forearms Pilot Study and Image Enhancement" , Int. Journ. of Biomed. Imag., Vol. 2013, Article 673027

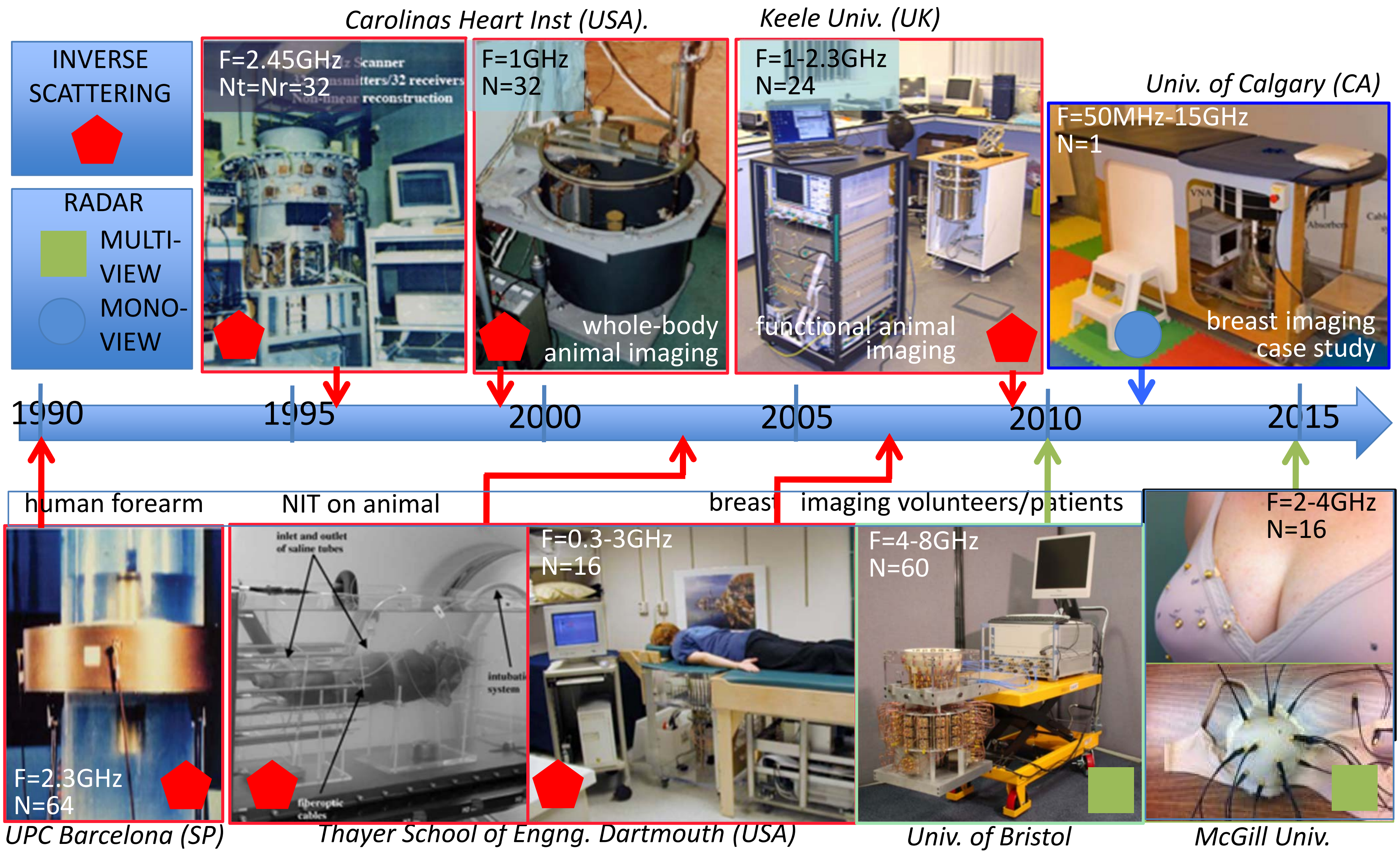
2015 REVIEW OF MiMed CONTRIBUTIONS (*)

FROM COMPUTER… A "LOSSY" PATH… *TO PATIENT BED*

Application	Algorithm [ref]	Numerical	Experimental	Human/Animal	Clinical Trial	Frequency
Heartbeat	Doppler Theorem [7], [8]	No	Yes	Yes	No	2.4 GHz, 5.8 GHz, 10 GHz
Blood Flow/Pressure	Tranmission meas. [57], [58]	Yes	Yes	Yes	No	2.5 GHz, 0.1-5 GHz
Cerebral Edema	Transmission meas. [5]	No	Yes	No	No	2.4 GHz
Brain Stroke	Transmission meas. [6]	No	Yes	Yes	Yes	0.3-3 GHz
Water Accumulation	Reflection meas. [60], [59]	Yes	Yes	Yes	No	915 MHz, 920 MHz, 3.1-10.6 GHz
Brain Imaging	Newton-type [4], [40]	Yes	No	No	No	Diff. Single freq. in 0.5-2.5 GHz
	Born Iterative [61]	Yes	No	No	No	600, 850, 1000 MHz
	Gauss-Newton [65]	Yes	No	No	No	1 GHz
	Confocal [55], [62]	Yes	Yes	No	No	1-4 GHz
Breast Imaging	Confocal [68], [69]	Yes	No	No	No	3.1-10.6 GHz
	TSAR [54], [70]	Yes	Yes	No	No	1-10 GHz
	Space-time Beamforming [71]	No	Yes	No	No	1-11 GHz
	Two stage Capon Beamforming [72]	Yes	No	No	No	UWB
	Newton-type [73], [74]	No	Yes	Yes	Yes	Single freq. in 300-900 MHz, 2 GHz
	Conjugate Gradient Method [75]	Yes	No	No	No	2, 3.5, 5 GHz
	Gauss-Newton [65]	Yes	No	No	No	1 GHz
	DBIM [77]	Yes	No	No	No	0.5-3.5 GHz
	CSI [78]	Yes	No	No	No	1 GHz
Bone Imaging	Levenberg-Marquadt [9]	Yes	No	No	No	800 MHz
	Gauss-Newton [10]	Yes	Yes	Yes	No	1.3 GHz
Soft-Tissue	Newton/MR-CSI [57]	No	Yes	Yes	No	1 GHz
	TSAR [17]	Yes	Yes	No	No	50 Mz - 13.51 GHz
Heart Imaging	MGM [12], [14]	Yes	Yes	Yes	No	0.9 GHz
	Back-Projection [15], [16]	Yes	Yes	Yes	No	0.8-3 GHz
Arm Imaging	CSI [81]	No	Yes	Yes	No	0.8, 1, 1.2 GHz
	Gauss-Newton [65]	No	Yes	Yes	No	2.33 GHz
	Newton-Kantorovich [82]	No	Yes	Yes	No	434 MHz
Thorax	Newton-Kantorovich [82]	Yes	No	No	No	434 MHz
Localization	Levenberg-Marquadt [83]	Yes	No	No	No	403.5 MHz
Whole-Body (Dog)	3-D Gradient [84]	No	Yes	Yes	No	0.9 GHz
Leg (Pig)	Newton Gradient, MR-CSI [37]	No	Yes	Yes	No	0.9-2.05 GHz

(*) *"**On the Opportunities and Challenges in Microwave Medical Sensing and Imaging**», R. Chandra, H. Zhou, I. Balasingham and R.M. Narayanan, IEEE Trans. BioMedical Engineering, Vol. 62, N0 7,1667-1681, July 2015*

MICROWAVE SCANNERS FOR BIOMEDICAL ASSESSMENT SOME EXAMPLES…



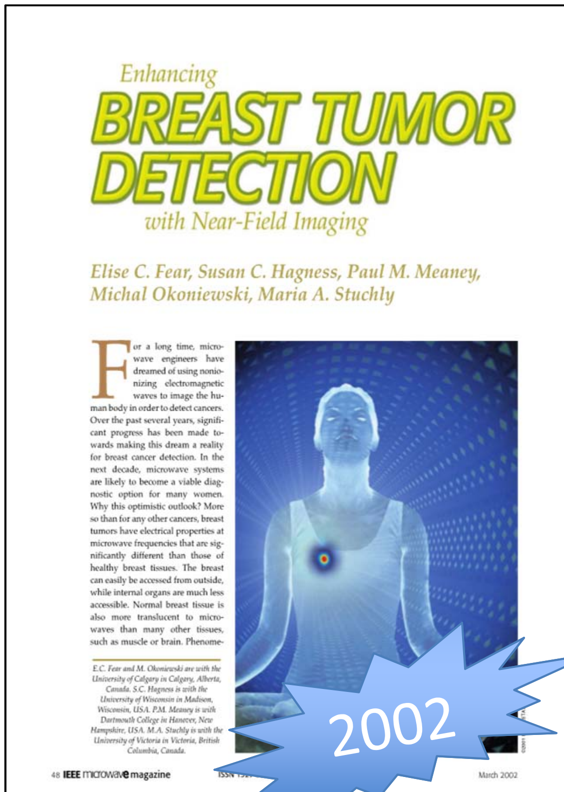
CONTENT

- 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

A TEST CASE: MICROWAVE-BASED BREAST IMAGING

DIELECTRIC IMAGING – AN ALTERNATIVE TO X-RAY MAMMO-GRAPHY,
A.W. Preece, M.F. Robinson, J.L. Green, M. Horrocks, Radiotherapy Center, Bristol
6TH SCIENTIFIC MEETING OF THE BRISTISH ONCOLOGICAL ASSOCIATION (BOA),
P 64, SUPPLEMENT XV: 25

1991



Enhancing
BREAST TUMOR DETECTION
with Near-Field Imaging

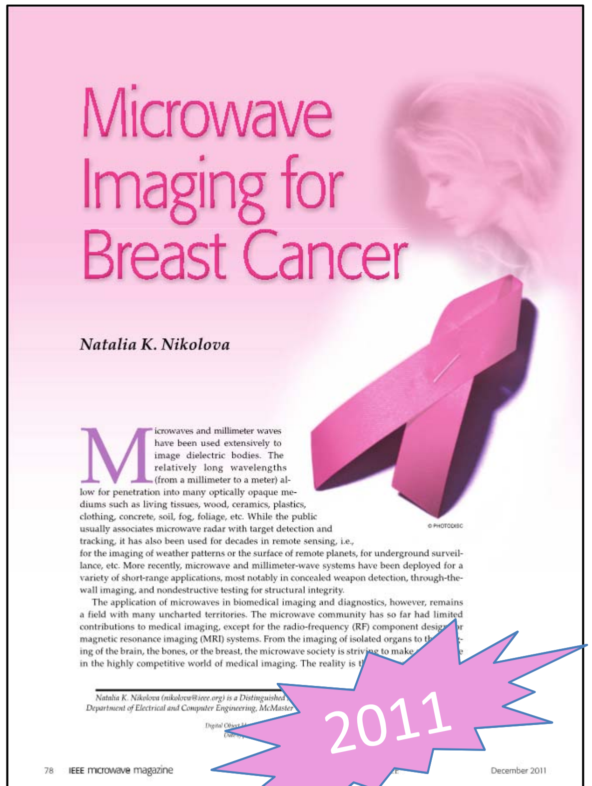
Elise C. Fear, Susan C. Hagness, Paul M. Meaney, Michal Okoniewski, Maria A. Stuchly

For a long time, microwave engineers have dreamed of using nonionizing electromagnetic waves to image the human body in order to detect cancers. Over the past several years, significant progress has been made towards making this dream a reality for breast cancer detection. In the next decade, microwave systems are likely to become a viable diagnostic option for many women. Why this optimistic outlook? More so than for any other cancers, breast tumors have electrical properties at microwave frequencies that are significantly different than those of healthy breast tissues. The breast can easily be accessed from outside, while internal organs are much less accessible. Normal breast tissue is also more translucent to microwaves than many other tissues, such as muscle or brain. Phenome-

E.C. Fear and M. Okoniewski are with the University of Calgary in Calgary, Alberta, Canada. S.C. Hagness is with the University of Wisconsin in Madison, Wisconsin, USA. P.M. Meaney is with Dartmouth College in Hanover, New Hampshire, USA. M.A. Stuchly is with the University of Victoria in Victoria, British Columbia, Canada.

48 IEEE microwave magazine ... March 2002

2002



Microwave Imaging for Breast Cancer

Natalia K. Nikolova

Microwaves and millimeter waves have been used extensively to image dielectric bodies. The relatively long wavelengths (from a millimeter to a meter) allow for penetration into many optically opaque mediums such as living tissues, wood, ceramics, plastics, clothing, concrete, soil, fog, foliage, etc. While the public usually associates microwave radar with target detection and tracking, it has also been used for decades in remote sensing, i.e., for the imaging of weather patterns or the surface of remote planets, for underground surveillance, etc. More recently, microwave and millimeter-wave systems have been deployed for a variety of short-range applications, most notably in concealed weapon detection, through-the-wall imaging, and nondestructive testing for structural integrity.

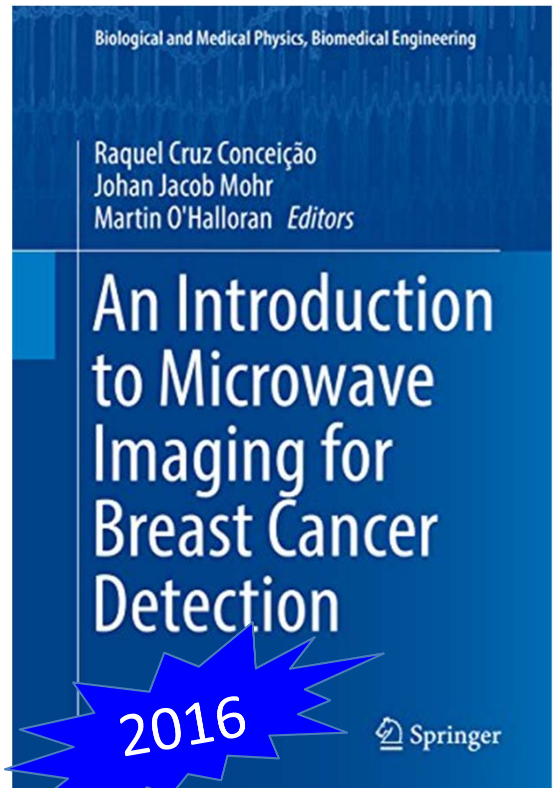
The application of microwaves in biomedical imaging and diagnostics, however, remains a field with many uncharted territories. The microwave community has so far had limited contributions to medical imaging, except for the radio-frequency (RF) component design for magnetic resonance imaging (MRI) systems. From the imaging of isolated organs to the ...ing of the brain, the bones, or the breast, the microwave society is striving to make ... in the highly competitive world of medical imaging. The reality is ...

© PHOTODISC

Natalia K. Nikolova (nikolova@ieee.org) is a Distinguished ... Department of Electrical and Computer Engineering, McMaster ...

78 IEEE microwave magazine ... December 2011

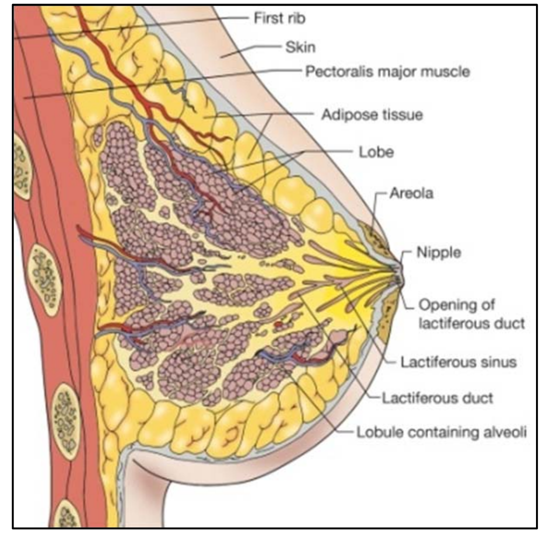
2011

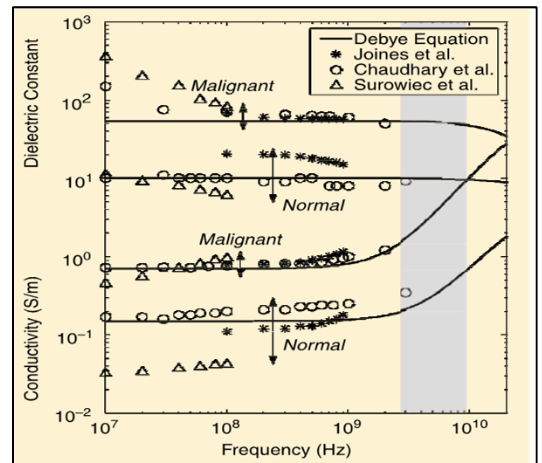


2016

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





igure 1. *Single-pole Debye curve fits of measured base-ine dielectric-properties data for normal and malignant reast tissue at radio and microwave frequencies [20].*

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)

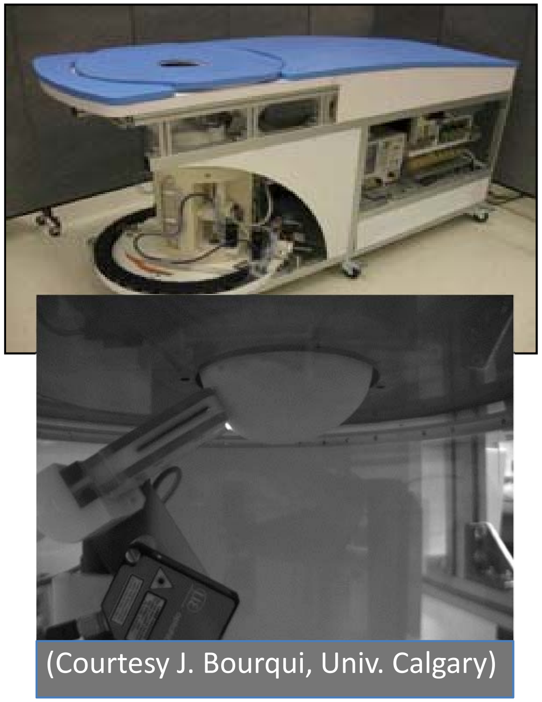
- EXPLOITATION OF THE CONTINUOUSLY GROWING COMPUTER POWER FOR:
  - DIELECTRIC CHARACTERIZATION
  - MRI-BASED NUMERICAL MODELS AND 3D-PRINTED PHANTOMS
  - ANTENNA DESIGN AND OPTIMIZATION ATTEMPTS
  - FREQUENCY/TIME DOMAIN RECEIVERS SIMULATION
  - MANY SCANNER GEOMETRIES
  - RECONSTRUCTION ALGORITHMS QUALITATIVE 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)

QUALITATIVE IMAGE RECONSTRUCTION



(Courtesy J. Bourqui, Univ. Calgary)

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)

QUANTITATIVE IMAGE RECONSTRUCTION

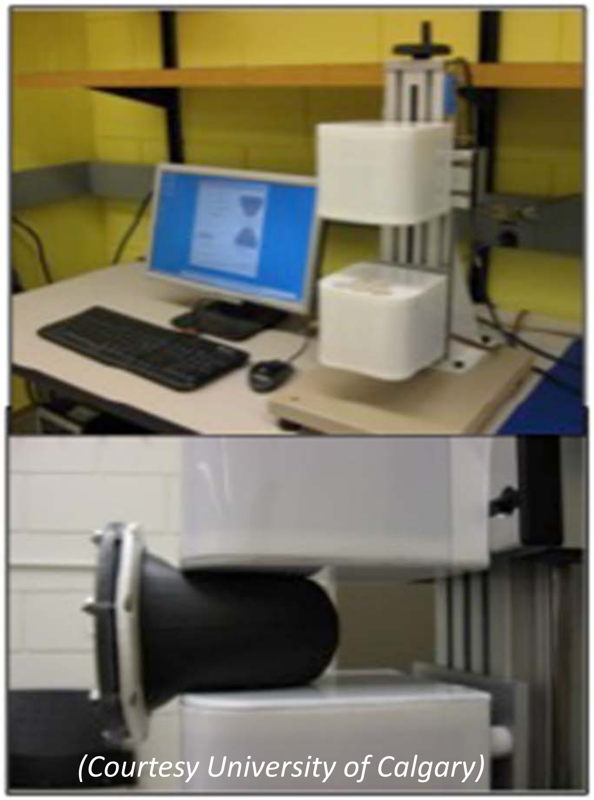
(Courtesy P.Meaney
Microwave Imaging Syst.Tech. Inc.)

MULTISTATIC TOMOGRAHY
MONO-FREQ. FROM **0.5 TO 2 GHZ**
CYLINDRICAL, 1**6 ANTENNAS**
(VERTICAL MONOPOLES)
MEDIUM IMMERSED BREAST
VERTICAL MECH. SCAN
THE LARGEST NUMBER OF EXAMS
SINCE 1995 (FEW HUNDREDS)

QUALITATIVE IMAGE RECONSTRUCTION

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)

EXAMPLES OF BREAST IMAGING SYSTEMS FOR VOLUNTEER/ PATIENT INVESTIGATIONS (2)

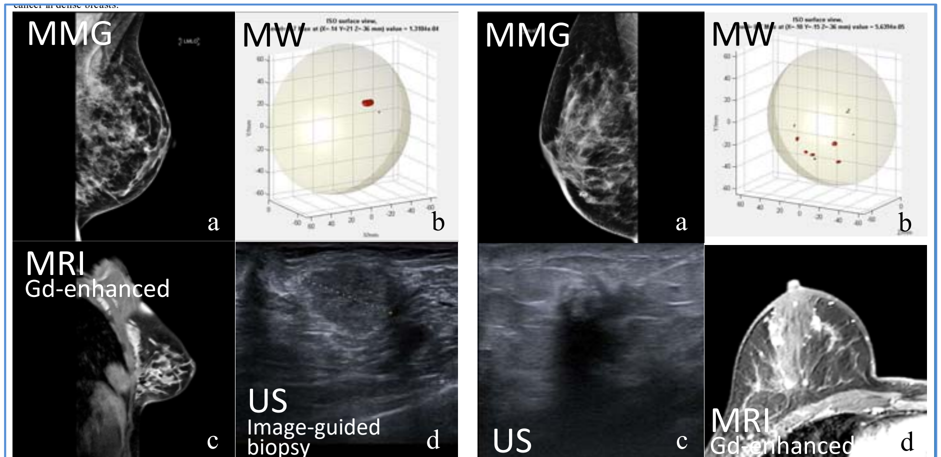

(Courtesy University of Calgary)

IN-VIVO MEASUREMENT
OF DIELECTRIC PERMITTIVITY


(Courtesy of McGill University)

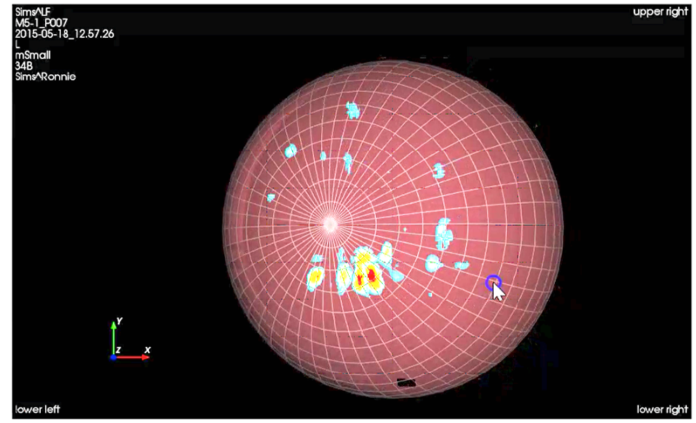
“PERSONNALIZED”
RESPONSE MONITORING

RECENT UWB RADAR CLINICAL RESULTS PRESENTED BY MICRIMA



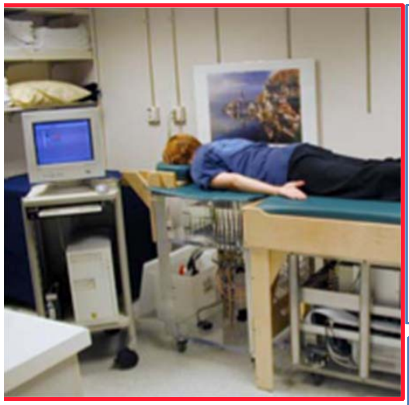
Results	Cases	Sensitivity Score (Ss)	Mean Age (Years)	Age Range	Cysts Ss	Cancer Ss	Other Ss
All	150	119 (79%)	52.5	16-89	42/54 (78%)	45/59 (76%)	29/36 (81%)
Pre-/Peri-	107	83 (78%)	38.0	16-60	36/48 (75%)	23/27 (85%)	26/32 (81%)
Post	41	36 (88%)	69.0	49-89	6/6 (100%)	27/33 (82%)	3/4 (75%)
Lucent	38	28 (74%)	64.5	40-89	3/5 (60%)	21/29 (72%)	4/4 (100%)
Dense	83	63 (76%)	50.0	19-81	33/41 (80%)	19/21 (90%)	15/19 (79%)
Unknown	29	25 (86%)	48.5	16-81	6/8 (75%)	10/10 (100%)	10/13 (77%)

M.Shere et al., "Radio-wave radar-based breast imaging system: an initial multi-site clinical evaluation",
Symposium Mammographicum, July 3-18, Liverpool, 2016



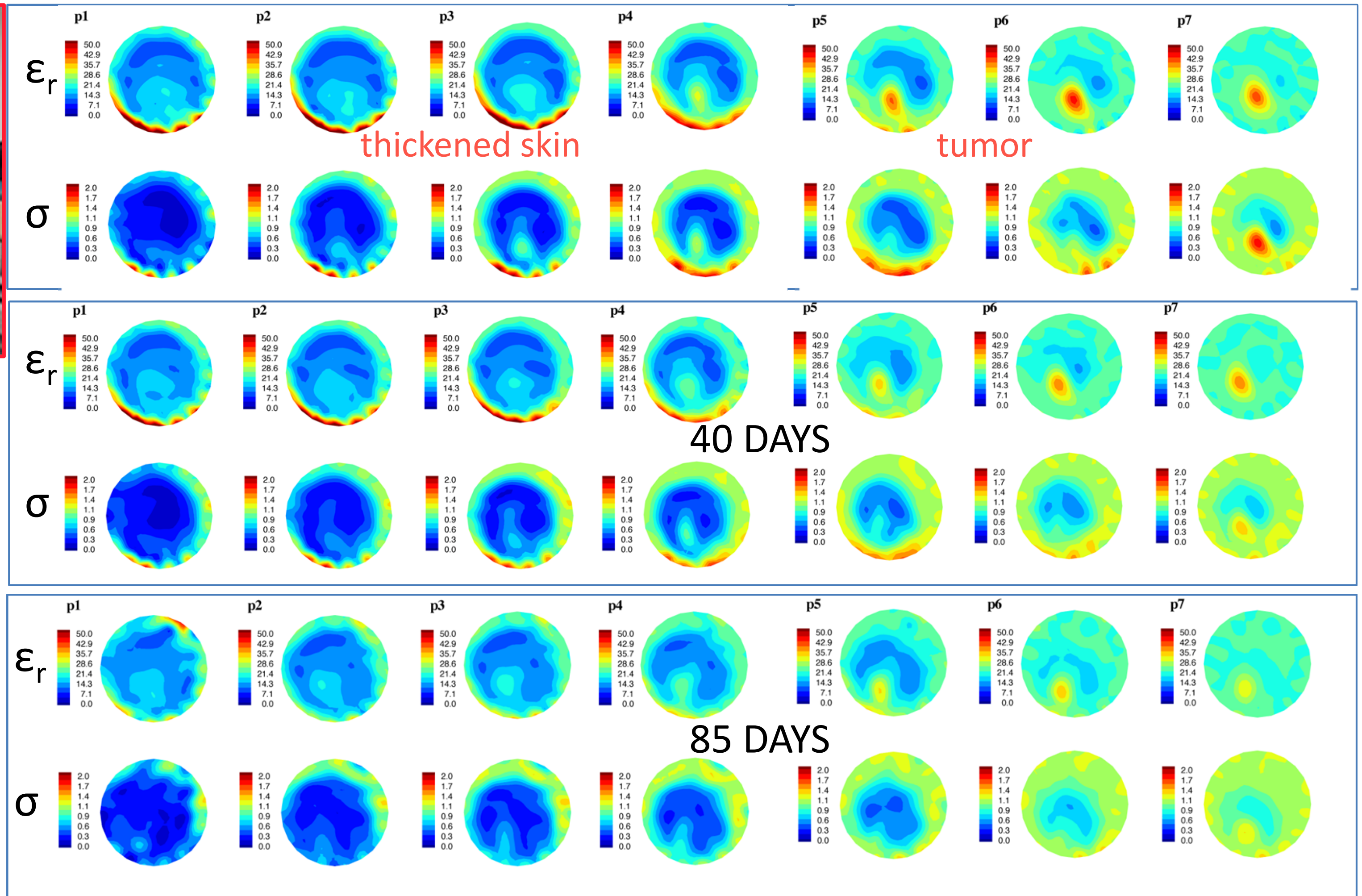
Representative 3D data set from MARIA system, showing location of high contrast regions that correspond to areas of abnormal radio frequency scattering attributable to the presence of lesions in the breast. The hemispherical display axes which correspond to the physical shape of the scanning head. (References: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

RECENT INVERSE SCATTERING CLINICAL RESULTS PRESENTED BY MIST



Thayer School of Engineering at Dartmouth College

NEOADJUVANT CHEMOTHERAPY MONITORING



Courtesy Paul Meaney
Microwave Imaging System Technologies, Inc.

P. Meaney, P.A. Kaufman, L.S. Muffly, M. Click, S.P. Poplack, W.A. Wells, G.N. Schwartz, R.M. di Florio-Alexander, T.D. Tosteson, Z. Li, S.D. Geimer, M.W. Fanning,T. Zhou, N.R. Epstein and K.D. Paulsen, "Microwave imaging for neoadjuvant chemotherapy monitoring: initial clinical experience", Breast Cancer Research 2013, and 2014 EuCAP, Workshop on Biomedical Engineering, University of Lisbon, Portugal – April 4-5, 2014

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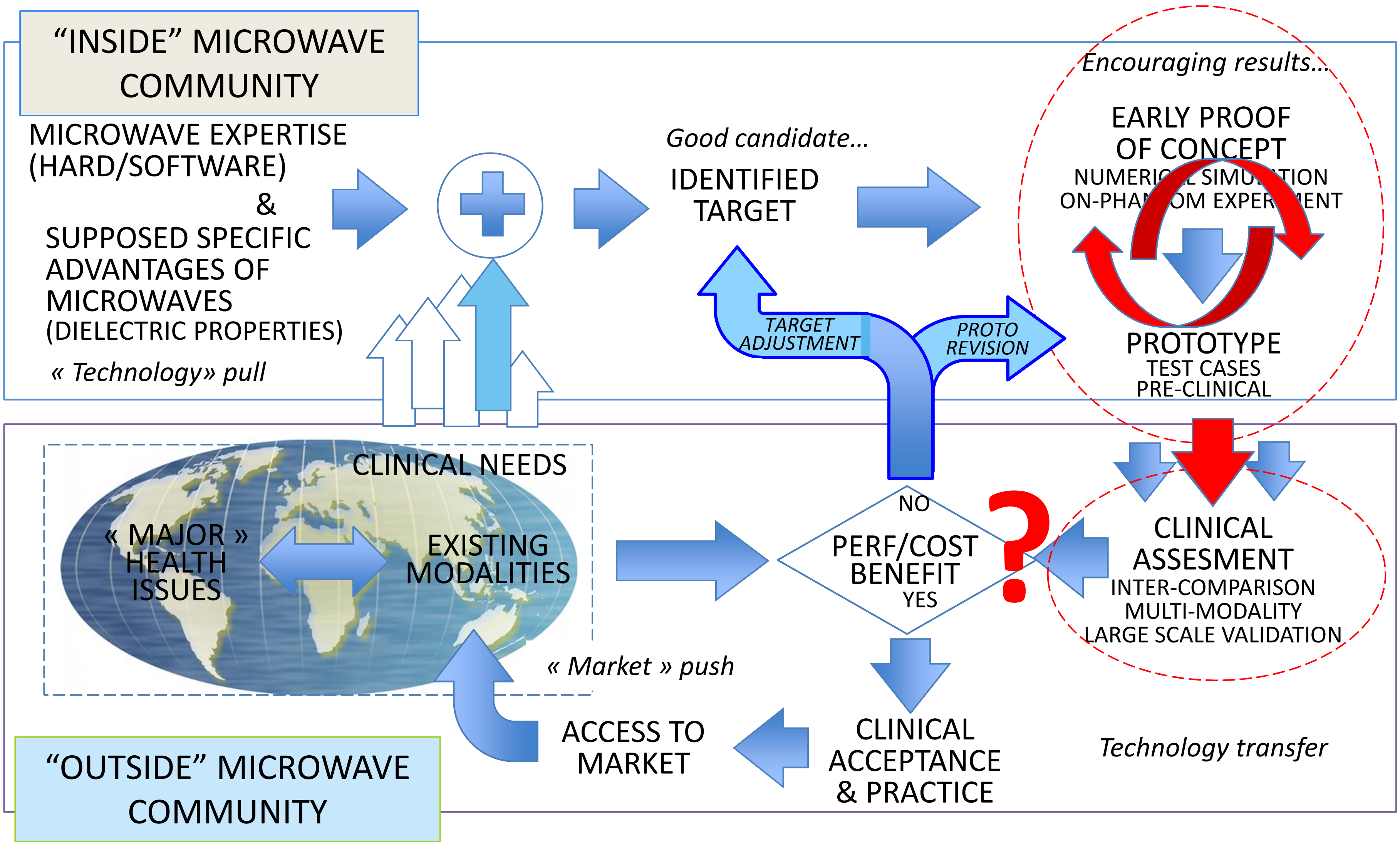
QUALITATIVE OR QUANTITATIVE ?

- 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 USUALLLY 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 NOR REQUIRE COMPLICATED COMPUTATION
  - NEGLECTS 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



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…

TO SUMMARIZE… (1)

ONE COULD HAVE BEEN SEEMING THAT MICROWAVES HAD REACHED THEIR LMITS

- 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…

- P. Meaney *(Dartmouth College)*
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- M. Persson, A. Fhager *(Chalmers University/ Medfield Diags)*
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- J. Lo Vetri, M. Ostadrahimi, P. Mojabi *(Univ. of Manitoba)*
- M. Popovic, E. Porter *(McGill University)*
- S. Semenov *(EM Tensor)*
- 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 (Polytecnico, 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.

A CONFESSED WEAKNESS RECOGNITION…

Microwaves for medical imaging: Some possible pathways for an accelerated progress towards clinical practice

Lorenzo Crocco, National Research Council, Napoli, Italy
New Horizons in Translational Medicine, Vol.2, Issue 2, p.62,Jan. 2015
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 OBreast Imaging System Manufacturing Companies
- rganizations
- 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 Emisssion 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