Master Degree in Information Technology Engineering for Health and Communication: Health Curriculum

Electromagnetic interactions and diagnostics

EM fields for biomedical diagnostics

EM fields for biomedical diagnostics

Table of contents:

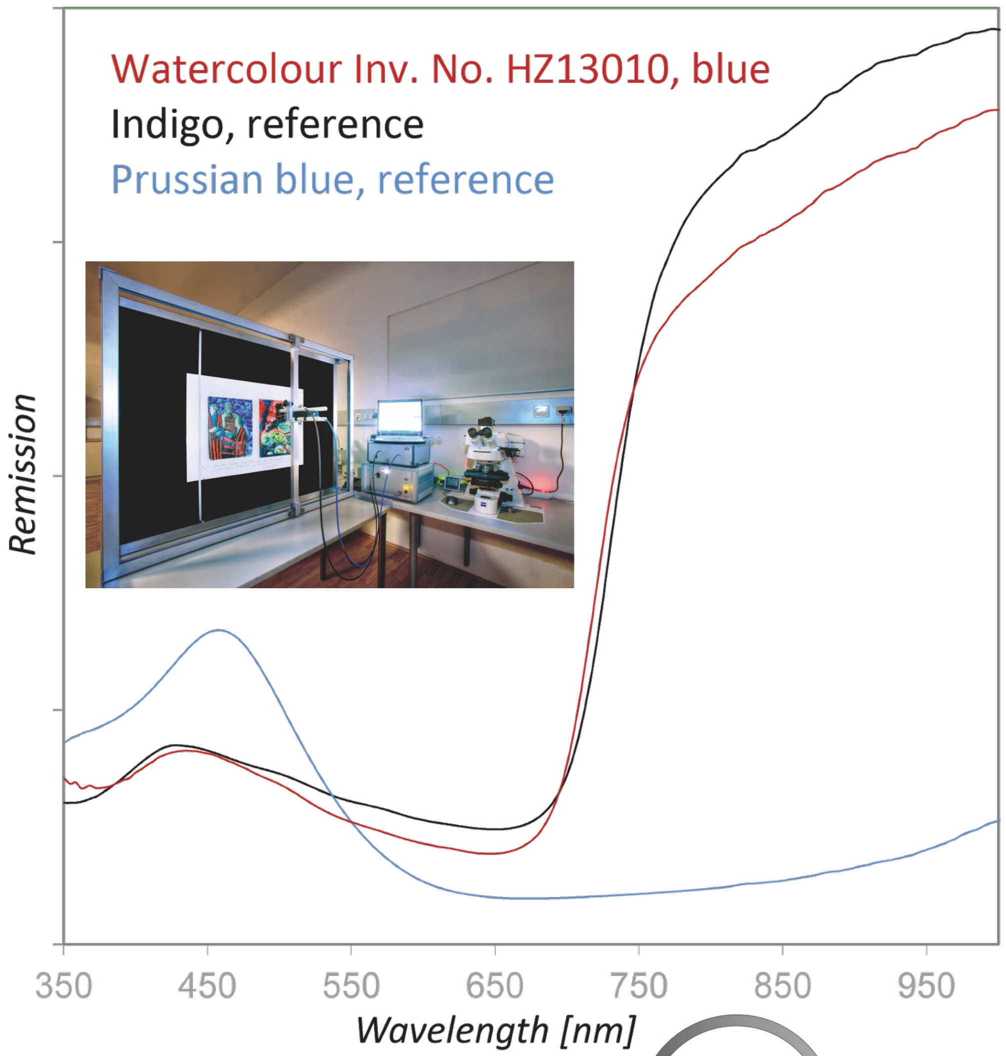
EM fields for biomedical diagnostics

Intro:

The EM diagnostics exploits the capability of EM waves to interact with the matter and, hence, to provide useful information on the target at different spatio-temporal scales. It founds applicability on:

- Civil infrastructures
- Water quality
- Cultural heritage
- Buried/hidden dangerous object detection
- ……..
- Biometry and biomedical applications

Watercolor by Rudolf von Alt, "Das Heidentor bei Petronell", 1837, Wien.

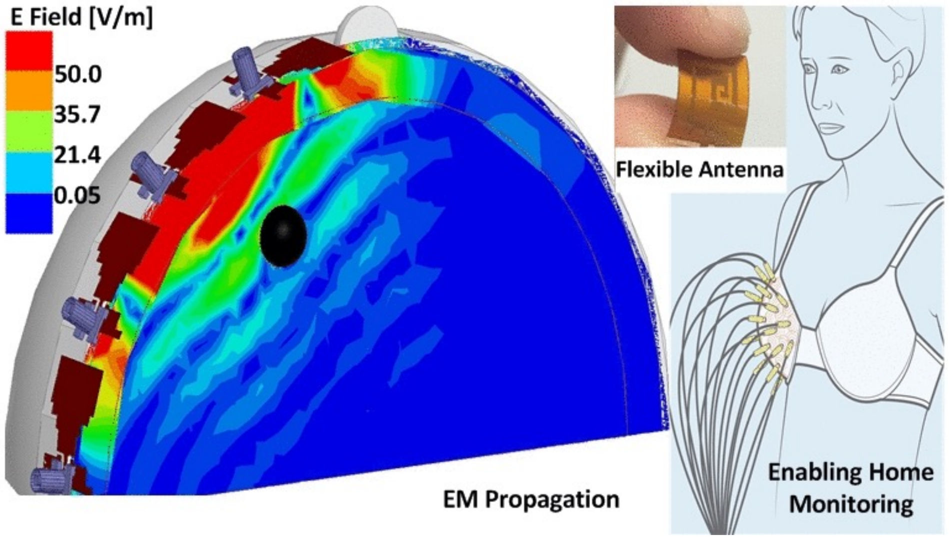


EM fields for biomedical diagnostics

Intro:

The aim of EM diagnostics is to improve, complement and even replace traditional diagnostics practices. Nowadays, EM diagnostics tools and technologies can provide:

- Non-destructive approach
- Less invasive analysis
- Better quality
- Earlier diagnosis



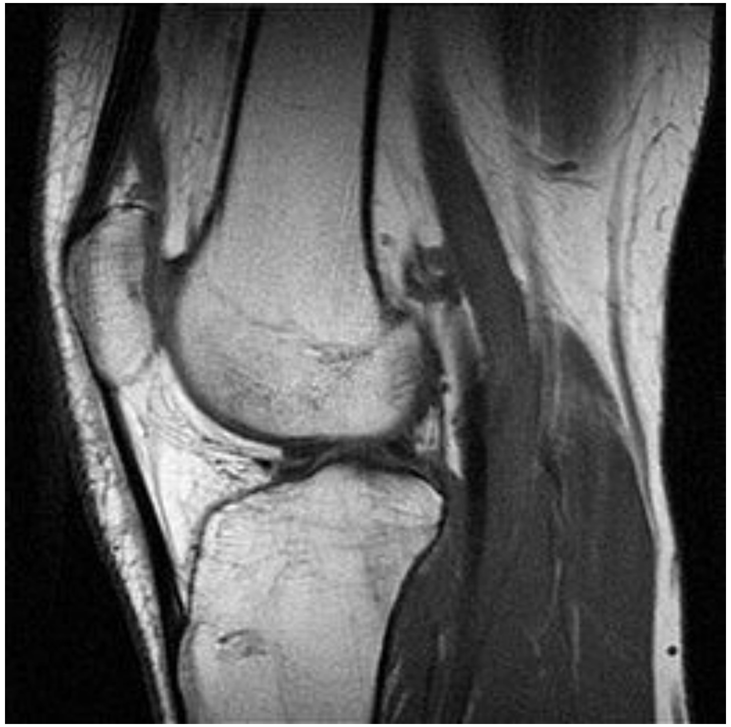
An example is the morphological and functional screening for early diagnosis of breast cancer, where healty and diseased tissues call for a different microwave scattering response.

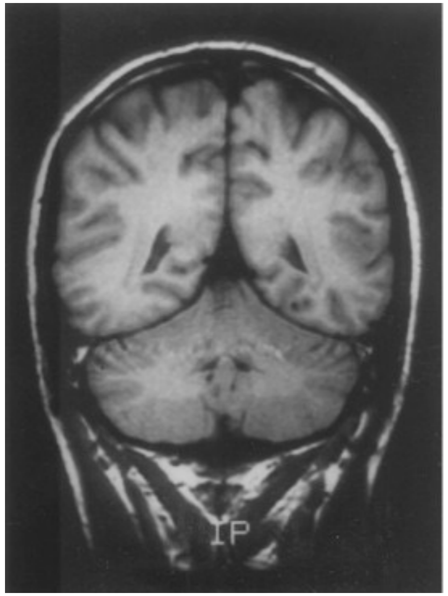
EM fields for biomedical diagnostics

Intro:

EM diagnosis tools:

- Radiography
- Computerized Axial Tomography
- Magnetic Resonance
- Positron emission tomography
- ....





EM fields for biomedical diagnostics

Intro:

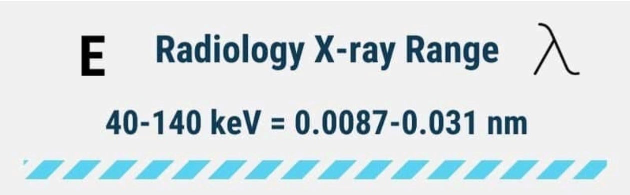
- Radiography

Resolution

Cost

Soft tissues

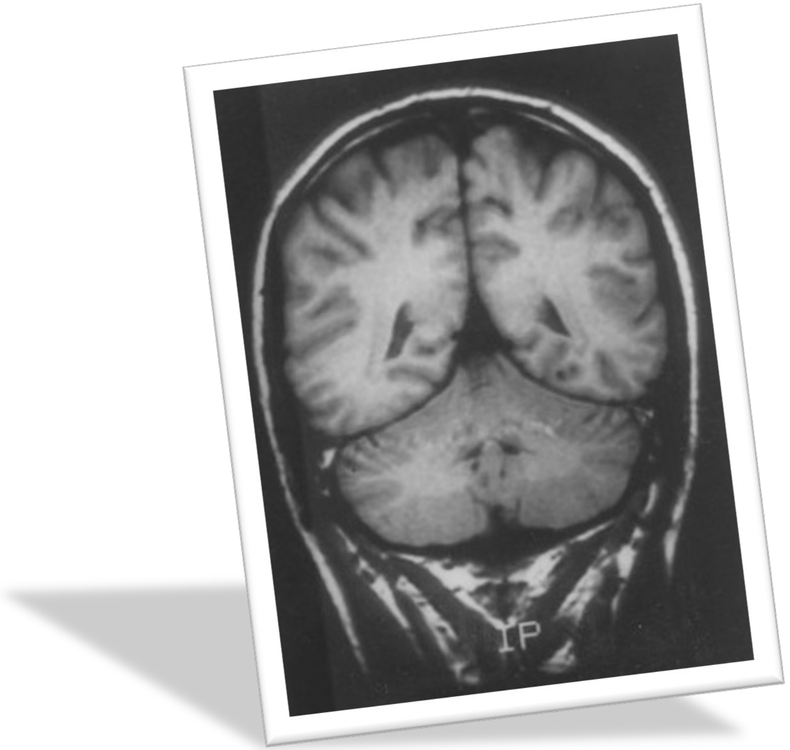
Ionizing rays



EM fields for biomedical diagnostics

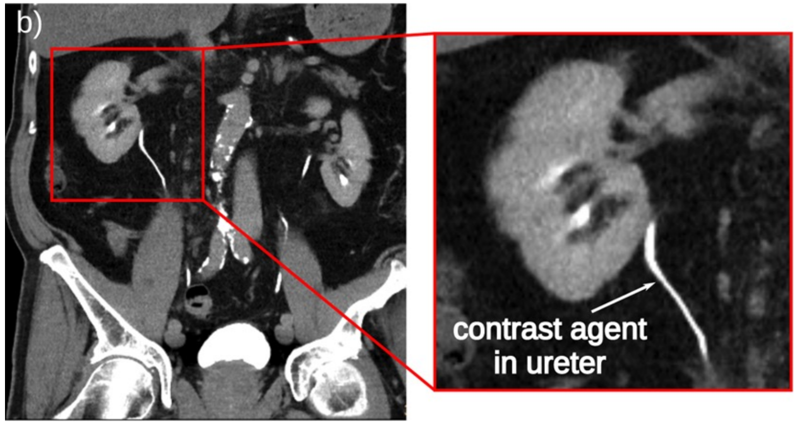
Intro:

- Computerized Axial Tomography



Generality

Ionizing rays
Contrast agent



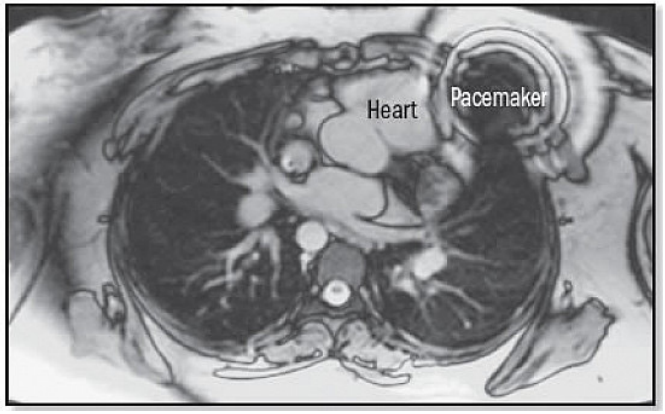
EM fields for biomedical diagnostics

Intro:

- Magnetic Resonance

Generality
Safety

Contrast agent
Cost
Pacemaker, etc.



EM fields for biomedical diagnostics

MWI: an overview

Microwave imaging is:

- ✓ Cost-effective
- ✓ Safe
- ✓ Non-invasive

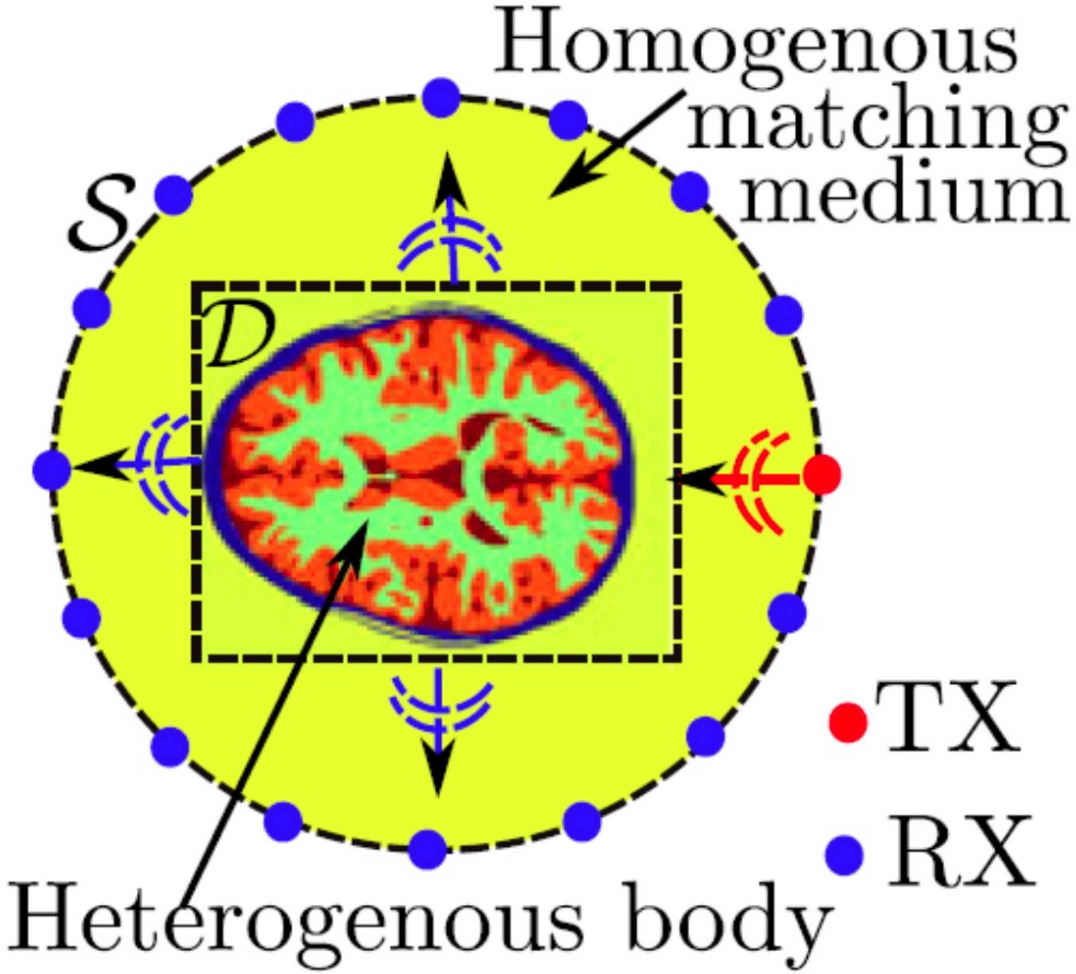
MWI can be used for diagnostics purposes of:

- ✓ Hearth (2006)
- ✓ Brain (2008)
- ✓ Breast (2011)
- ✓ Bones (2012)

EM fields for biomedical diagnostics

MWI: an overview

Microwave tomography: reconstruction, using a remote sensing approach, of EM parameters in a complex environment to identify potential anomalies and to characterize their morphological (location, shape, size) and dielectric (electric permittivity and conductivity, magnetic permeability).

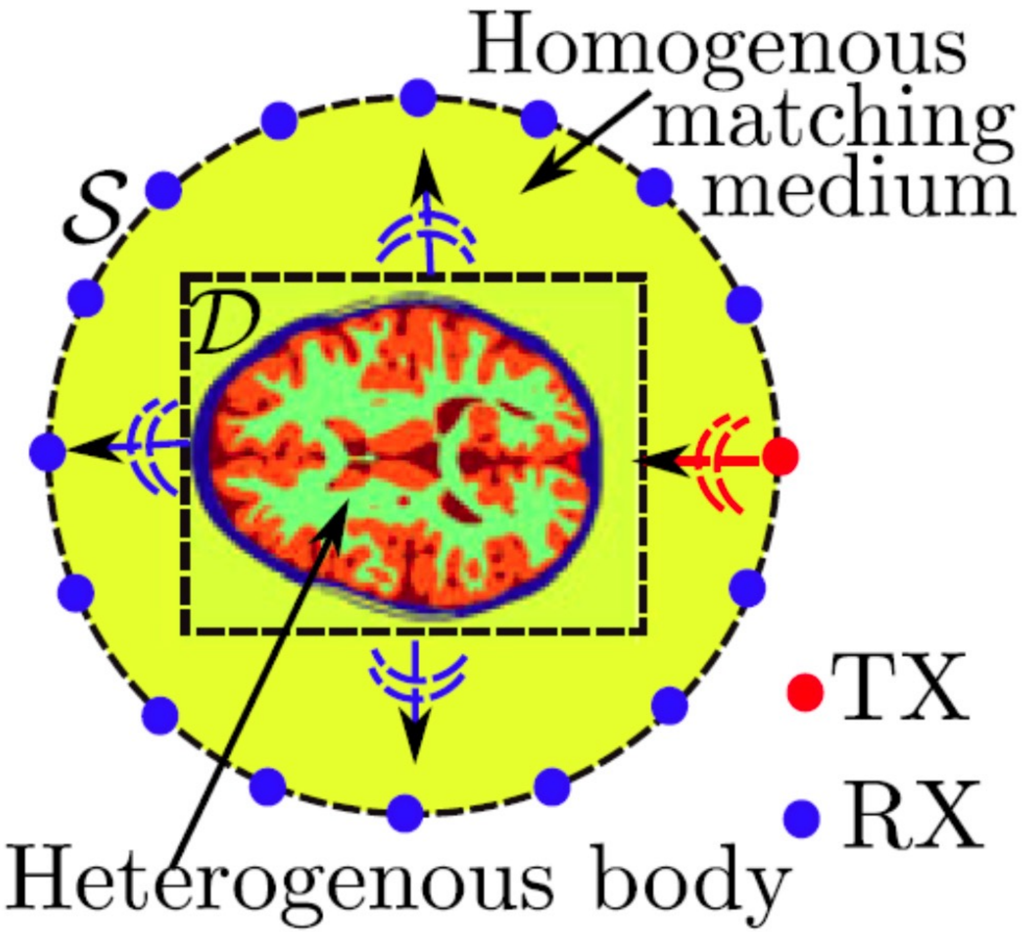


EM fields for biomedical diagnostics

MWI: an overview

✓ *MICROWAVE TOMOGRAPHY:*

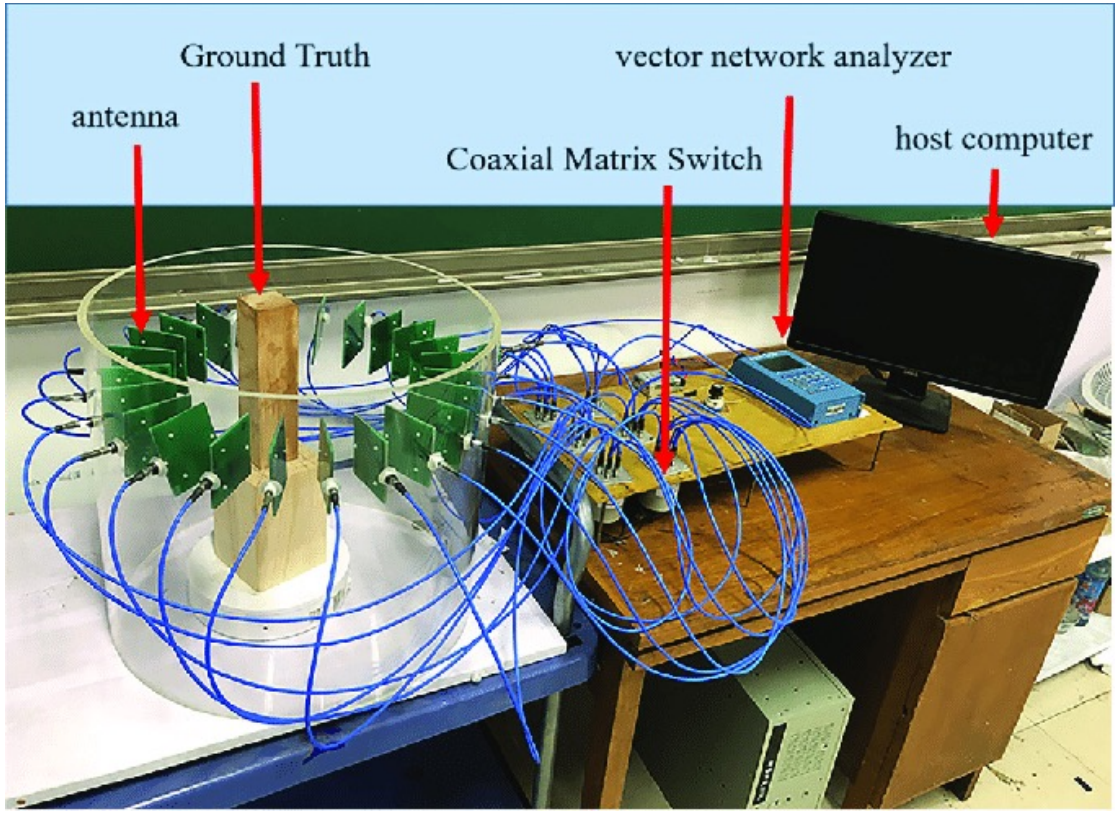
- Comprehensive mapping
- Inverse scattering
- Computational efforts
- Ill-posed mathematical problem

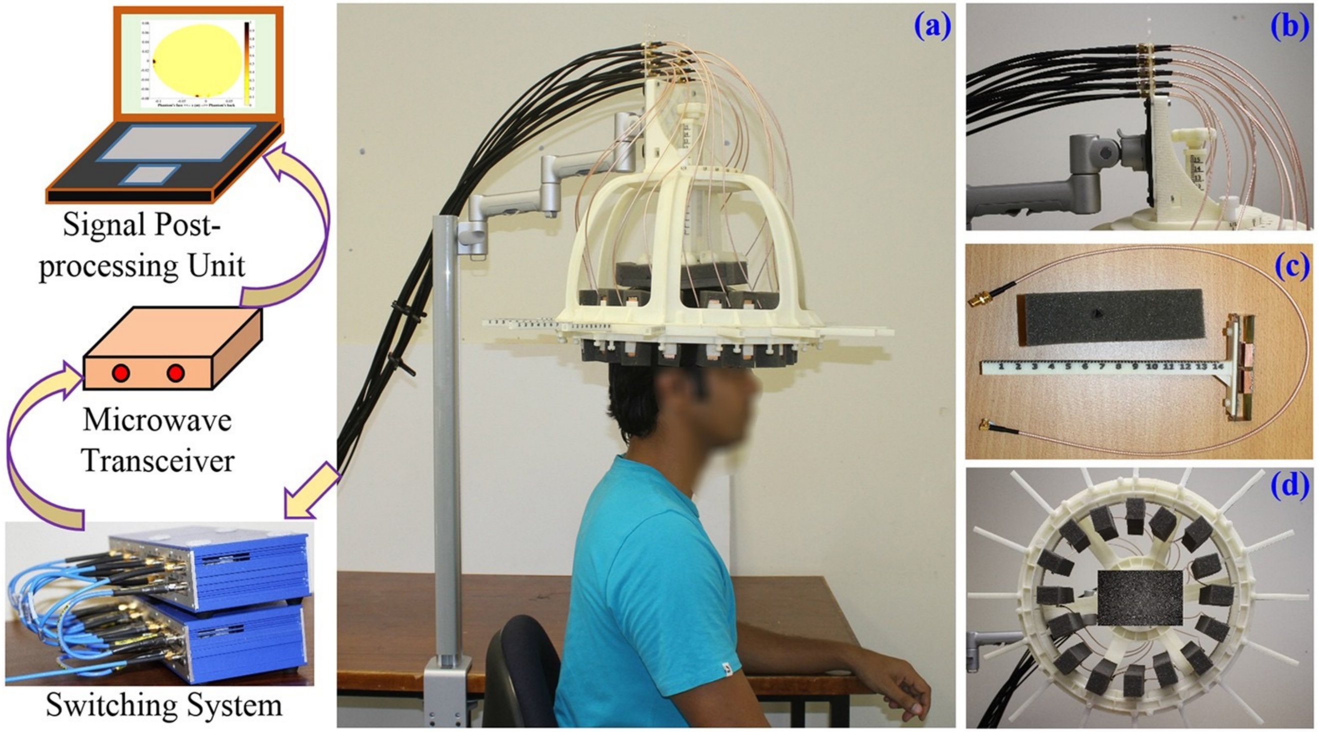


EM fields for biomedical diagnostics

MWI: an overview

- ✓ *MICROWAVE TOMOGRAPHY:*



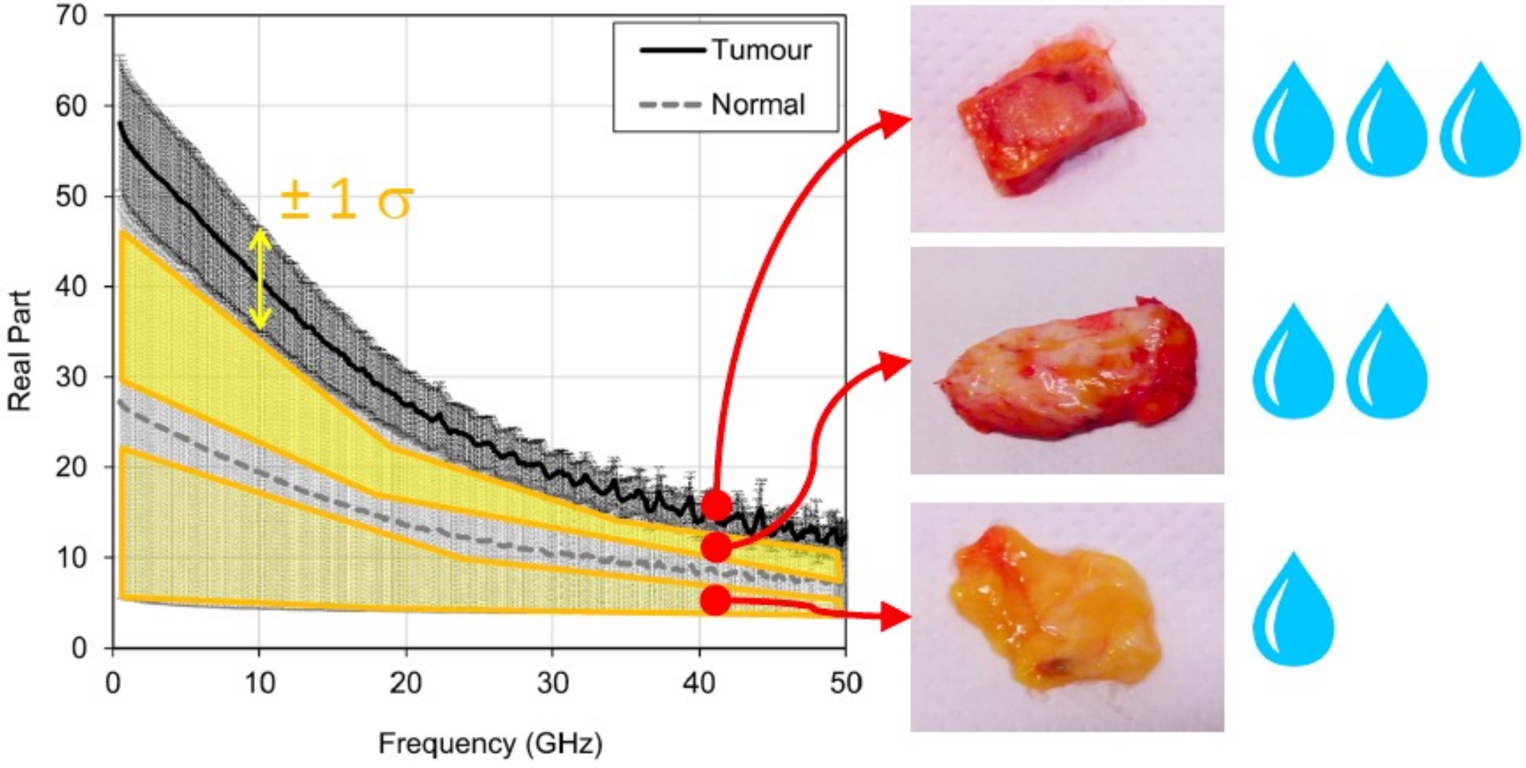


EM fields for biomedical diagnostics

MWI: an overview

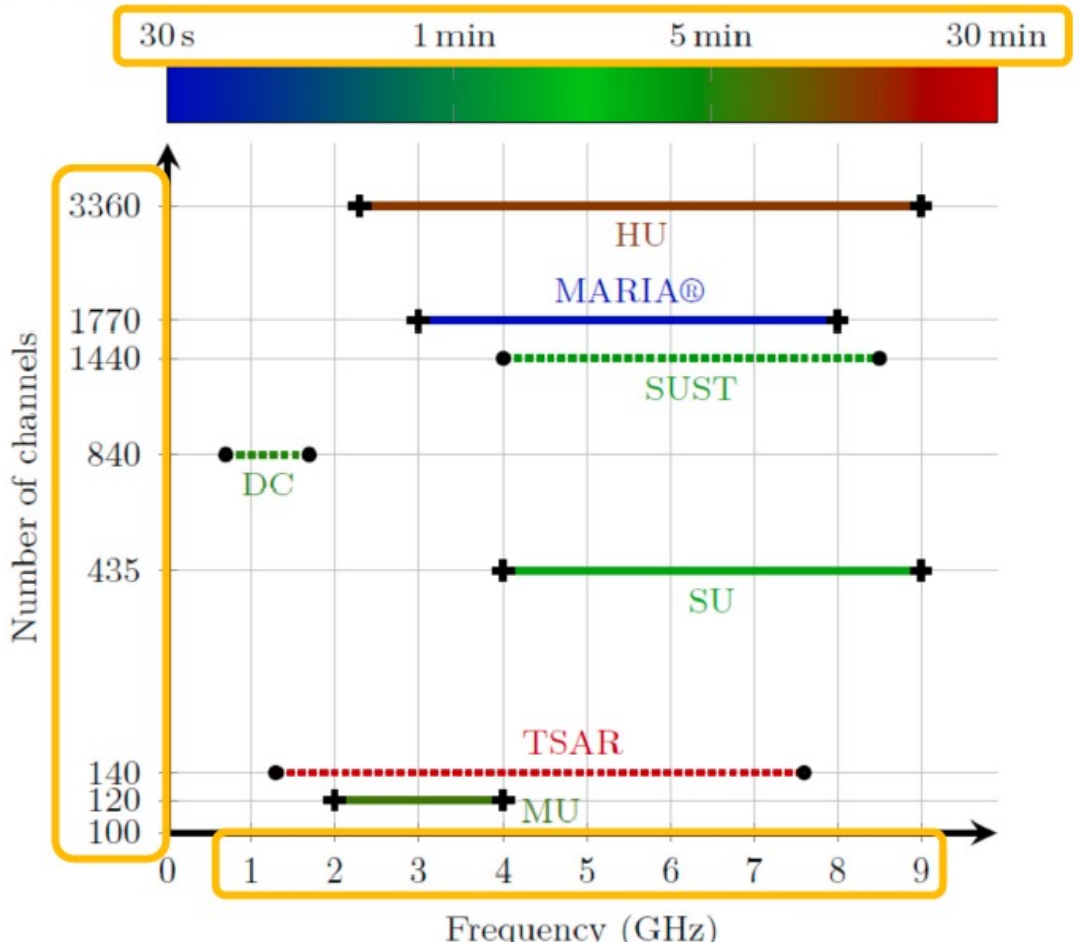
✓ *MWI: BREAST TUMOUR*

- ➢ Evaluation of dielectric properties contrast between healthy and neoplastic tissues
- ➢ Changes in water content
- ➢ Propagation losses through tissues



EM fields for biomedical diagnostics

MWI: an overview



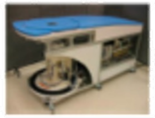
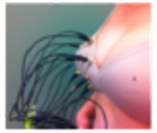
✓ *MWI: BREAST TUMOUR*

- *Key imaging parameters*
  - ➢ Central frequency
  - ➢ Bandwidth
  - ➢ # Antennas (Image quality)
  - ➢ Scan time (Usability)
- *Quality features*
  - ➢ Penetration depth (LF → High penetration)
  - ➢ Resolution (HF, Large BW → Fine resolution)

EM fields for biomedical diagnostics

MWI: an overview

✓ *MWI: BREAST TUMOUR*

	DC [15]–[19]	MARIA® [20]–[26]	TSAR [27]–[30]	HU [33]	SUST [34]	MU [35], [36]	SU [37], [38]
							
Largest trial:	150	223	8 patients	5 patients	11 patients	13 volunteers	2 patients
Scan time:	5 min	10 s	30 min	14 min	4 min	5 min	3 min
Position:	prone	prone	prone	supine	prone	seated	prone
Coupling:	medium	shell	medium	shell	medium	shell	shell
Table:	✓	✓	✓	✗	✓	✗	✓
Array type:	synthetic	hardware	synthetic	synthetic	synthetic	stationary	hardware
Acquisition:	frequency	frequency	frequency	time	frequency	time	frequency
Antenna:	monopole	slot	vivaldi	planar slot	horn	microstrip	stacked patch
Multistatic:	✓	✓	✗	✓	✓	✓	✓
Artefact:	—	rotation	neighbour-based	averaging	adaptive filtering	differential	rotation
Imaging:	tomography	IDAS	DAS	DAS	DAS	DAS	DAS

MWI: an overview

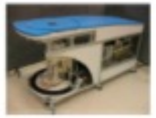
✓ *MWI: BREAST TUMOUR*

	DC [15]–[19]	MARIA® [20]–[26]	TSAR [27]–[30]	HU [33]	SUST [34]	MU [35], [36]	SU [37], [38]
Largest trial:	150	223					
Scan time:	5 min	10 s					
Position:	prone	prone					
Coupling:	medium	shell					
Table:	✓	✓					
Array type:	synthetic	hardware					
Acquisition:	frequency	frequency					
Antenna:	monopole	slot					
Multistatic:	✓	✓					
Artefact:	—	rotation	ne				
Imaging:	tomography	IDAS					

EM fields for biomedical diagnostics

MWI: an overview

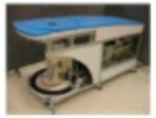
✓ *MWI: BREAST TUMOUR*

	DC [15]–[19]	MARIA® [20]–[26]	TSAR [27]–[30]	HU [33]	SUST [34]	MU [35], [36]	SU [37], [38]
							
Largest trial:	150	223	8 patients	5 patients	11 patients	13 volunteers	2 patients
Scan time:	5 min	10 s	30 min	14 min	4 min	5 min	3 min
Position:	prone	prone	prone	supine	prone	seated	prone
Coupling:	medium	shell	medium	shell	medium	shell	shell
Table:	✓	✓	✓	✗	✓	✗	✓
Array type:	synthetic	hardware	synthetic	synthetic	synthetic	stationary	hardware
Acquisition:	frequency	frequency	frequency	time	frequency	time	frequency
Antenna:	monopole	slot	vivaldi	planar slot	horn	microstrip	stacked patch
Multistatic:	✓	✓	✗	✓	✓	✓	✓
Artefact:	—	rotation	neighbour-based	averaging	adaptive filtering	differential	rotation
Imaging:	tomography	IDAS	DAS	DAS	DAS	DAS	DAS

EM fields for biomedical diagnostics

MWI: an overview

✓ *MWI: BREAST TUMOUR*

	DC [15]–[19]	MARIA® [20]–[26]	TSAR [27]–[30]	HU [33]	SUST [34]	MU [35], [36]	SU [37], [38]
							
Largest trial:	150	223	8 patients	5 patients	11 patients	13 volunteers	2 patients
Scan time:	5 min	10 s	30 min	14 min	4 min	5 min	3 min

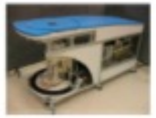
$N = k_B N_{BW} T_{eq}$ [W]

Faster scans are noisier, hence slower scans can provide better images if other articfacts’ sources, i. e., the ones associated to motion effects, can be calibrated out.

EM fields for biomedical diagnostics

MWI: an overview

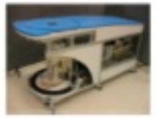
✓ *MWI: BREAST TUMOUR*

	DC [15]–[19]	MARIA® [20]–[26]	TSAR [27]–[30]	HU [33]	SUST [34]	MU [35], [36]	SU [37], [38]
							
Largest trial:	150	223	8 patients	5 patients	11 patients	13 volunteers	2 patients
Scan time:	5 min	10 s	30 min	14 min	4 min	5 min	3 min
Position:	prone	prone	prone	supine	prone	seated	prone
Coupling:	medium	shell	medium	shell	medium	shell	shell
Table:	✓	✓	✓	✗	✓	✗	✓
Array type:	synthetic	hardware	synthetic	synthetic	synthetic	stationary	hardware
Acquisition:	frequency	frequency	frequency	time	frequency	time	frequency
Antenna:	monopole	slot	vivaldi	planar slot	horn	microstrip	stacked patch
Multistatic:	✓	✓	✗	✓	✓	✓	✓
Artefact:	—	rotation	neighbour-based	averaging	adaptive filtering	differential	rotation
Imaging:	tomography	IDAS	DAS	DAS	DAS	DAS	DAS

EM fields for biomedical diagnostics

MWI: an overview

✓ *MWI: BREAST TUMOUR*

	DC [15]–[19]	MARIA® [20]–[26]	TSAR [27]–[30]	HU [33]	SUST [34]	MU [35], [36]	SU [37], [38]
							

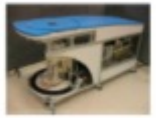
Actual antennas can be physically located («hardware») or «virtual» antennas can be synthesized from actual radiators.

Array type:	synthetic	hardware	synthetic	synthetic	synthetic	stationary	hardware
Acquisition:	frequency	frequency	frequency	time	frequency	time	frequency
Antenna:	monopole	slot	vivaldi	planar slot	horn	microstrip	stacked patch
Multistatic:	✓	✓	✗	✓	✓	✓	✓
Artefact:	—	rotation	neighbour-based	averaging	adaptive filtering	differential	rotation
Imaging:	tomography	IDAS	DAS	DAS	DAS	DAS	DAS

EM fields for biomedical diagnostics

MWI: an overview

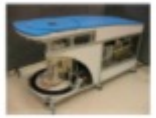
✓ *MWI: BREAST TUMOUR*

	DC [15]–[19]	MARIA® [20]–[26]	TSAR [27]–[30]	HU [33]	SUST [34]	MU [35], [36]	SU [37], [38]
							
Largest trial:	150	223	8 patients	5 patients	11 patients	13 volunteers	2 patients
Scan time:	5 min	10 s	30 min	14 min	4 min	5 min	3 min
Position:	prone	prone	prone	supine	prone	seated	prone
Coupling:	medium	shell	medium	shell	medium	shell	shell
Table:	✓	✓	✓	✗	✓	✗	✓
Array type:	synthetic	hardware	synthetic	synthetic	synthetic	stationary	hardware
Acquisition:	frequency	frequency	frequency	time	frequency	time	frequency
Antenna:	monopole	slot	vivaldi	planar slot	horn	microstrip	stacked patch
Multistatic:	✓	✓	✗	✓	✓	✓	✓
Artefact:	—	rotation	neighbour-based	averaging	adaptive filtering	differential	rotation
Imaging:	tomography	IDAS	DAS	DAS	DAS	DAS	DAS

EM fields for biomedical diagnostics

MWI: an overview

✓ *MWI: BREAST TUMOUR*

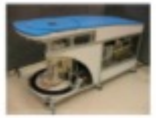
	DC [15]–[19]	MARIA® [20]–[26]	TSAR [27]–[30]	HU [33]	SUST [34]	MU [35], [36]	SU [37], [38]
							
Acquisition:	frequency	frequency	frequency	time	frequency	time	frequency
Antenna:	monopole	slot	vivaldi	planar slot	horn	microstrip	stacked patch
Multistatic:	✓	✓	✗	✓	✓	✓	✓
Artefact:	—	rotation	neighbour-based	averaging	adaptive filtering	differential	rotation
Imaging:	tomography	IDAS	DAS	DAS	DAS	DAS	DAS

All frequencies in the bandwidth can be simultaneously and independently generated or they are used to generate a pulse in time domain.

EM fields for biomedical diagnostics

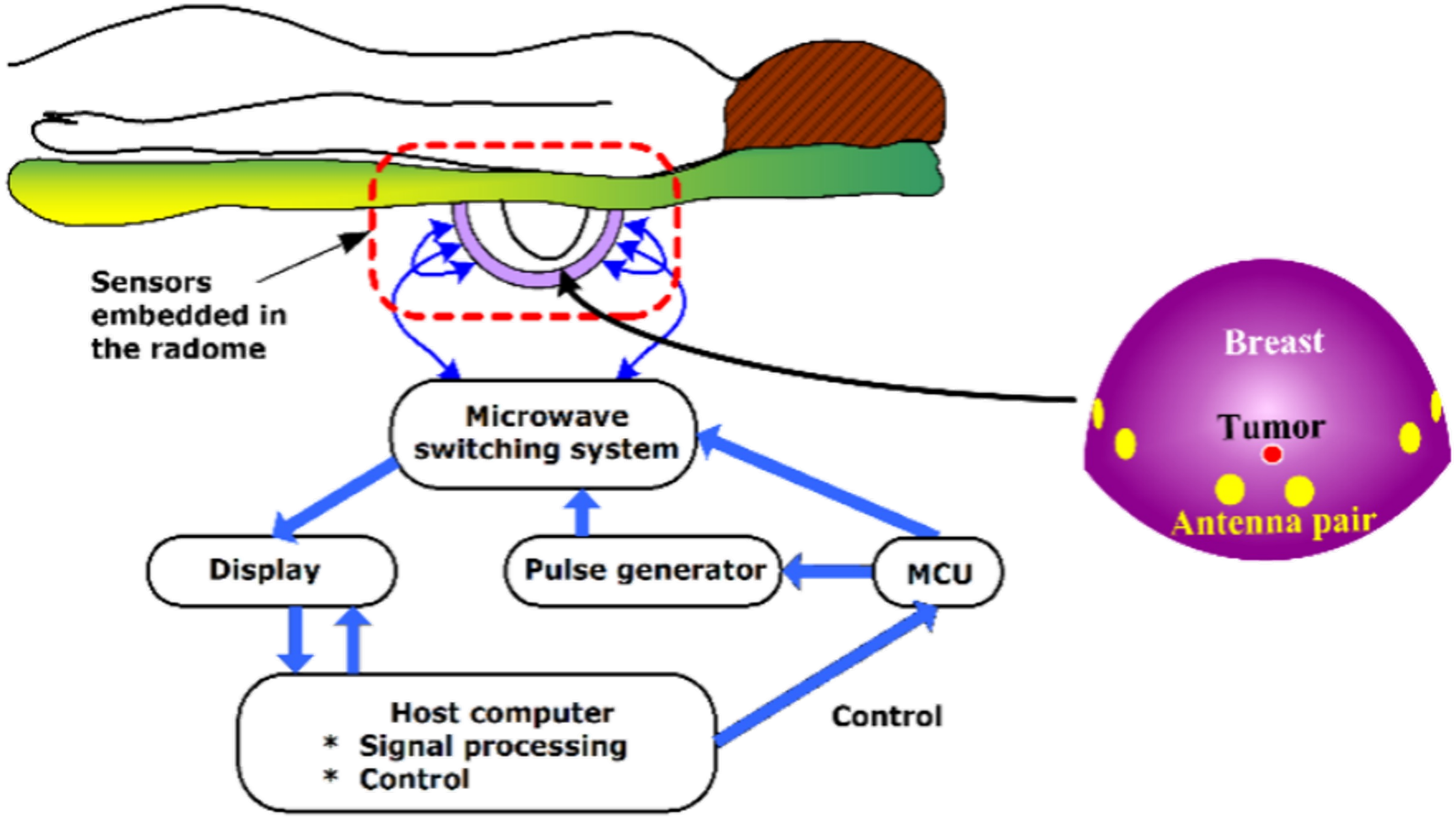
MWI: an overview

✓ *MWI: BREAST TUMOUR*

	DC [15]–[19]	MARIA® [20]–[26]	TSAR [27]–[30]	HU [33]	SUST [34]	MU [35], [36]	SU [37], [38]
							
Largest trial:	150	223	8 patients	5 patients	11 patients	13 volunteers	2 patients
Scan time:	5 min	10 s	30 min	14 min	4 min	5 min	3 min
Position:	prone	prone	prone	supine	prone	seated	prone
Coupling:	medium	shell	medium	shell	medium	shell	shell
Table:	✓	✓	✓	✗	✓	✗	✓
Array type:	synthetic	hardware	synthetic	synthetic	synthetic	stationary	hardware
Acquisition:	frequency	frequency	frequency	time	frequency	time	frequency
Antenna:	monopole	slot	vivaldi	planar slot	horn	microstrip	stacked patch
Multistatic:	✓	✓	✗	✓	✓	✓	✓
Artefact:	—	rotation	neighbour-based	averaging	adaptive filtering	differential	rotation
Imaging:	tomography	IDAS	DAS	DAS	DAS	DAS	DAS

EM fields for biomedical diagnostics

MWI: an overview



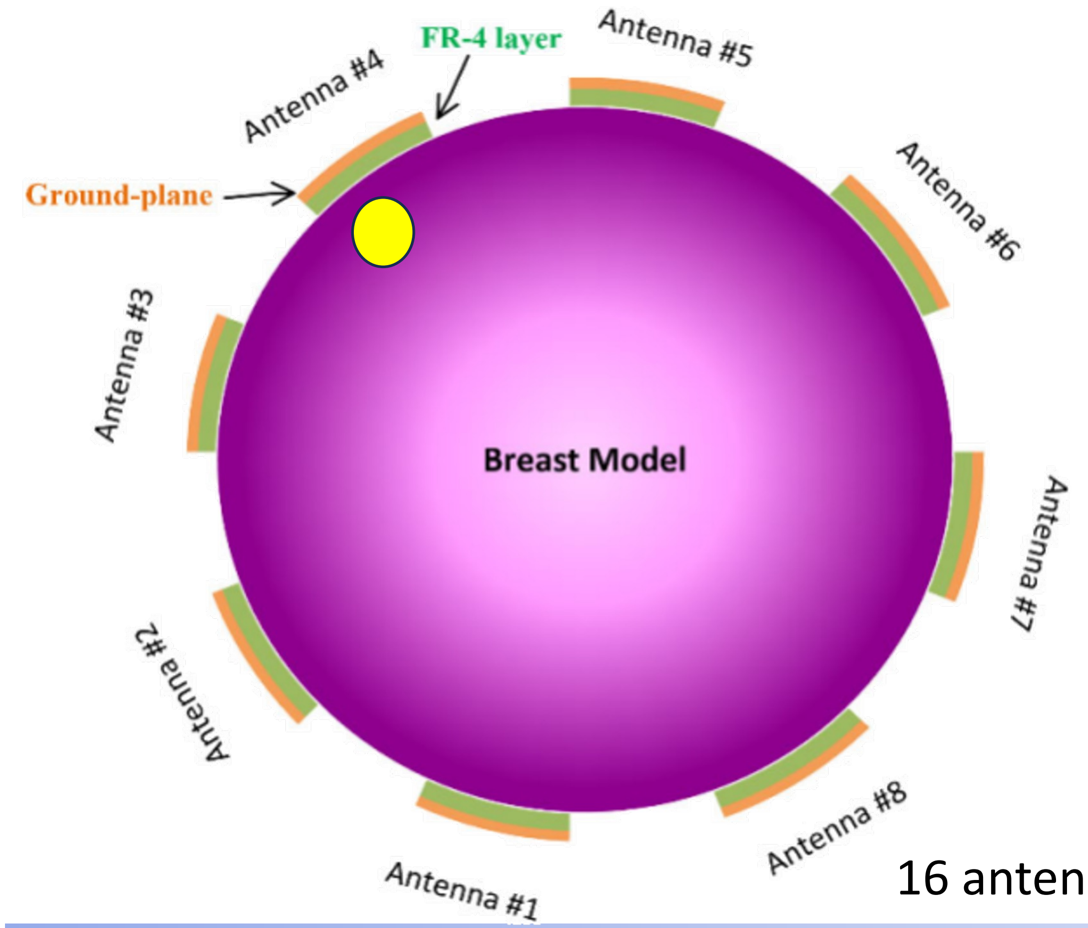
✓ *MWI: BREAST TUMOUR*

Imaging setup:

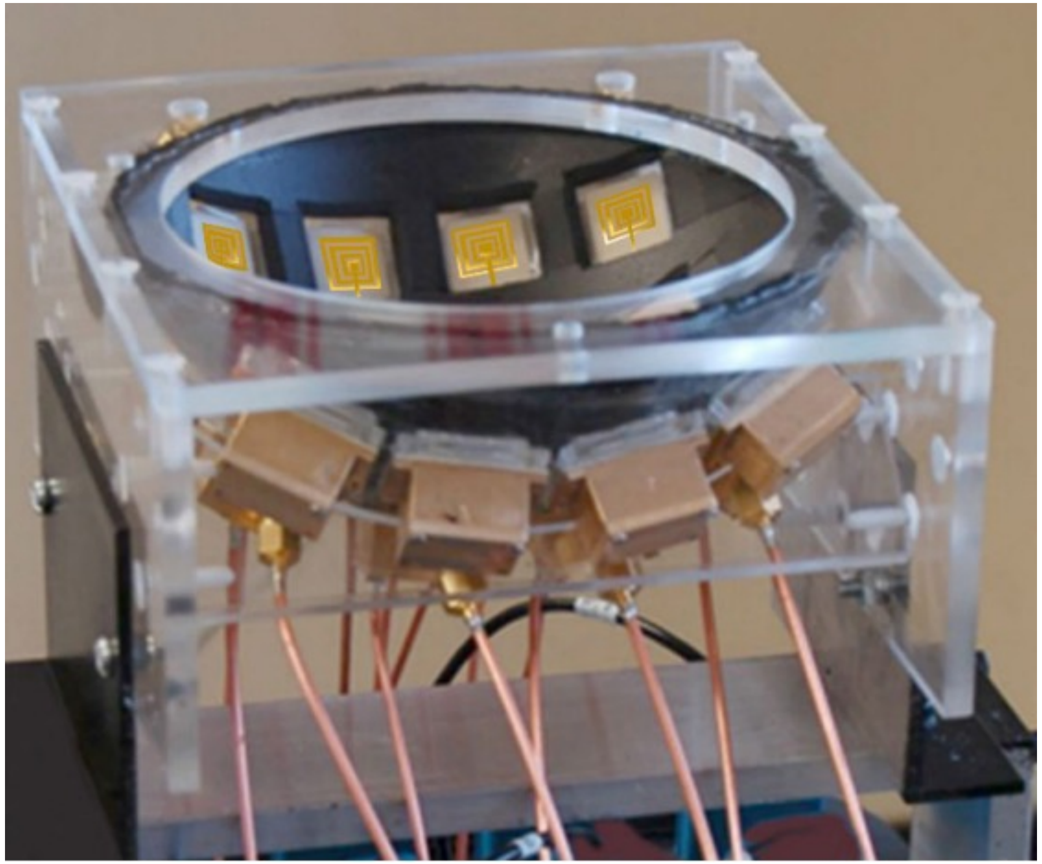
- $\sigma_{skin} = 4$ S/m, $\varepsilon_{r\,skin} = 36$
- $th_{skin} = 2$ mm
- $\sigma_{breast} = 0.15$ S/m
- $\varepsilon_{s\,breast} = 10$, $\varepsilon_{\infty\,breast} = 7$
- $\sigma_{tumour} = 0.7$ S/m
- $\varepsilon_{s\,tumour} = 54$, $\varepsilon_{\infty\,tumour} = 4$
- $d_{tumour} = 5$ mm

EM fields for biomedical diagnostics

MWI: an overview



✓ *MWI: BREAST TUMOUR*

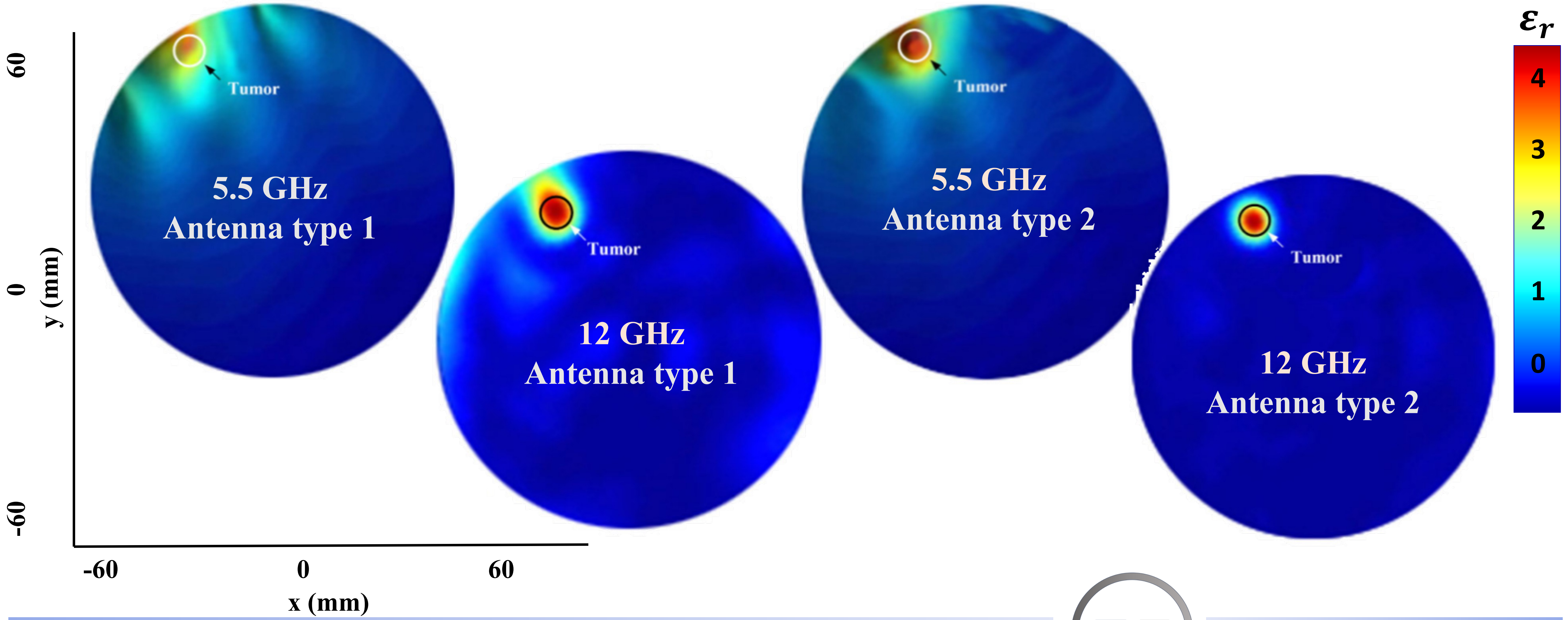


16 antennas, 240 signals per scan

EM fields for biomedical diagnostics

MWI: an overview

✓ *MWI: BREAST TUMOUR*



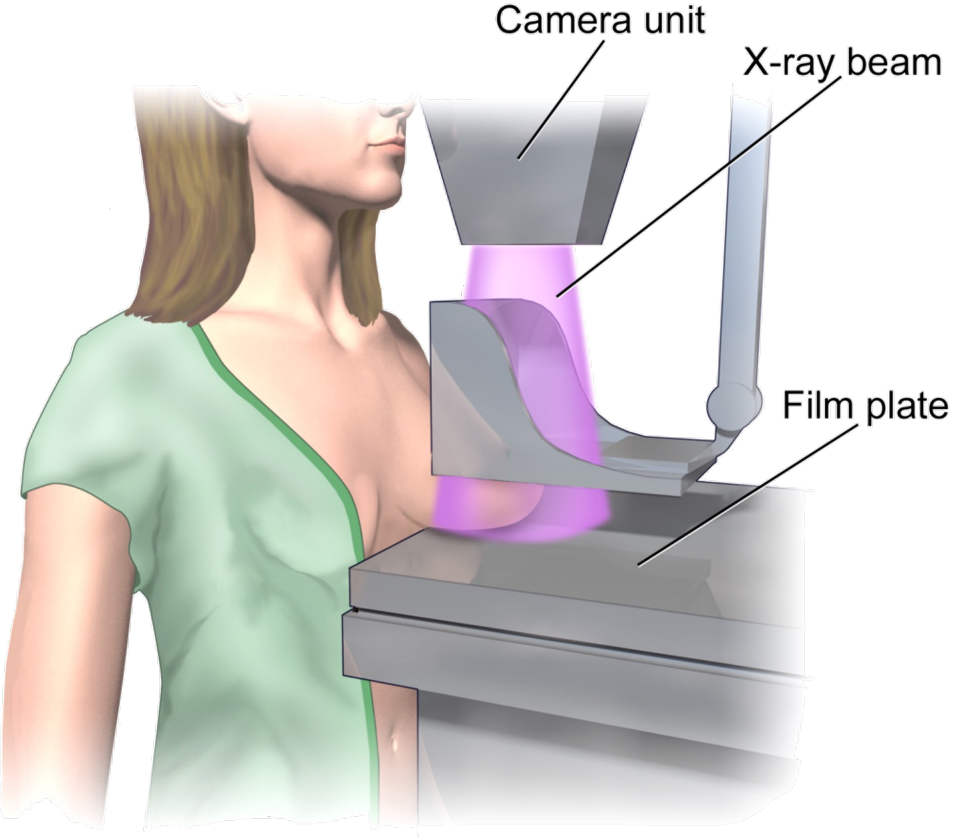
EM fields for biomedical diagnostics

MWI: an overview

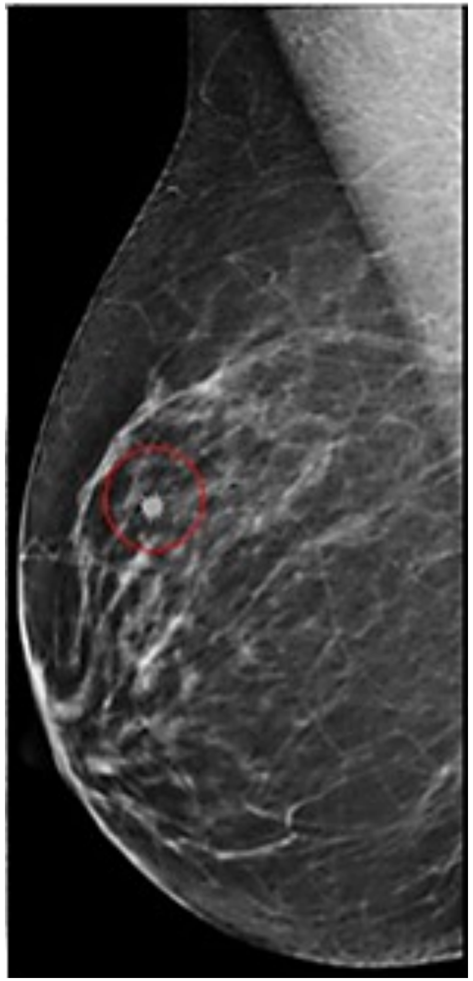
✓ *MWI: BREAST TUMOUR*

Comfortable
Safe
Simple to use
Cost-effective
Mobility

Spatial resolution
1 mm versus 0.05 mm



Mammogram



Showcase: brain stroke

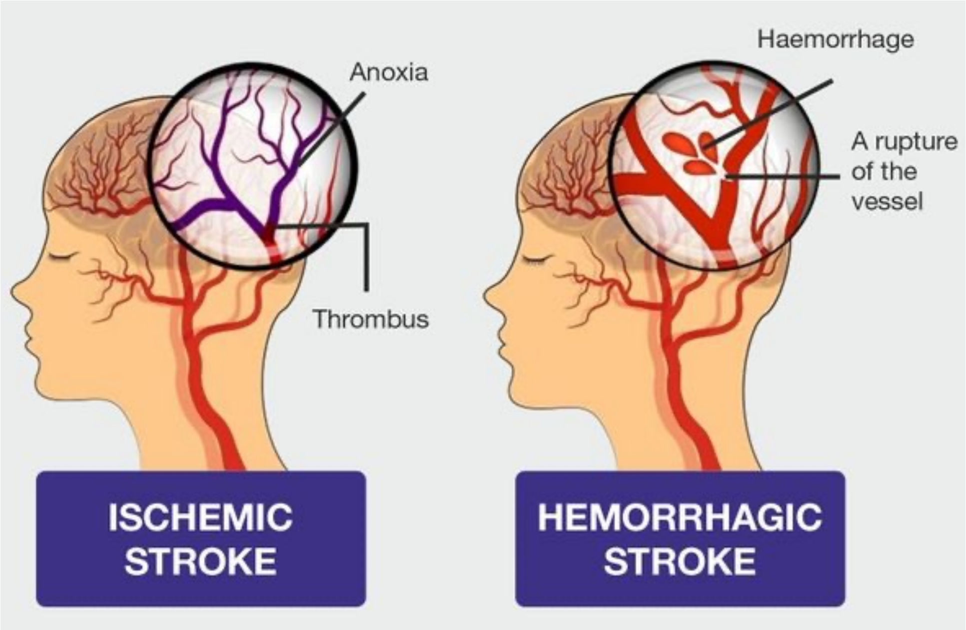
✓ *Intro*

Goals:

- Early detection of the pathology's onset;
- Evolution monitoring after the initial diagnosis.

Two types of brain strokes:

- Hemorrhagic (a bleeding into the brain occurs)
- Ischemic (tissue necrosis due to blood blockage)



MWI is a potential candidate to replace traditional diagnostics methods as MRI (costly) and CT (unsafe) for continuous post-event monitoring.

Showcase: brain stroke

✓ *Intro*

MWI approach is based on the significant differences between the dielectric properties of healthy and hemorrhagic/ischemic brain tissues. The MWI problem is complicated by the fact that the relationship between the measurable electric field and the dielectric properties of the head is non-linear and strongly ill-posed.

In this framework, two kinds of MWI methodologies can be identified:

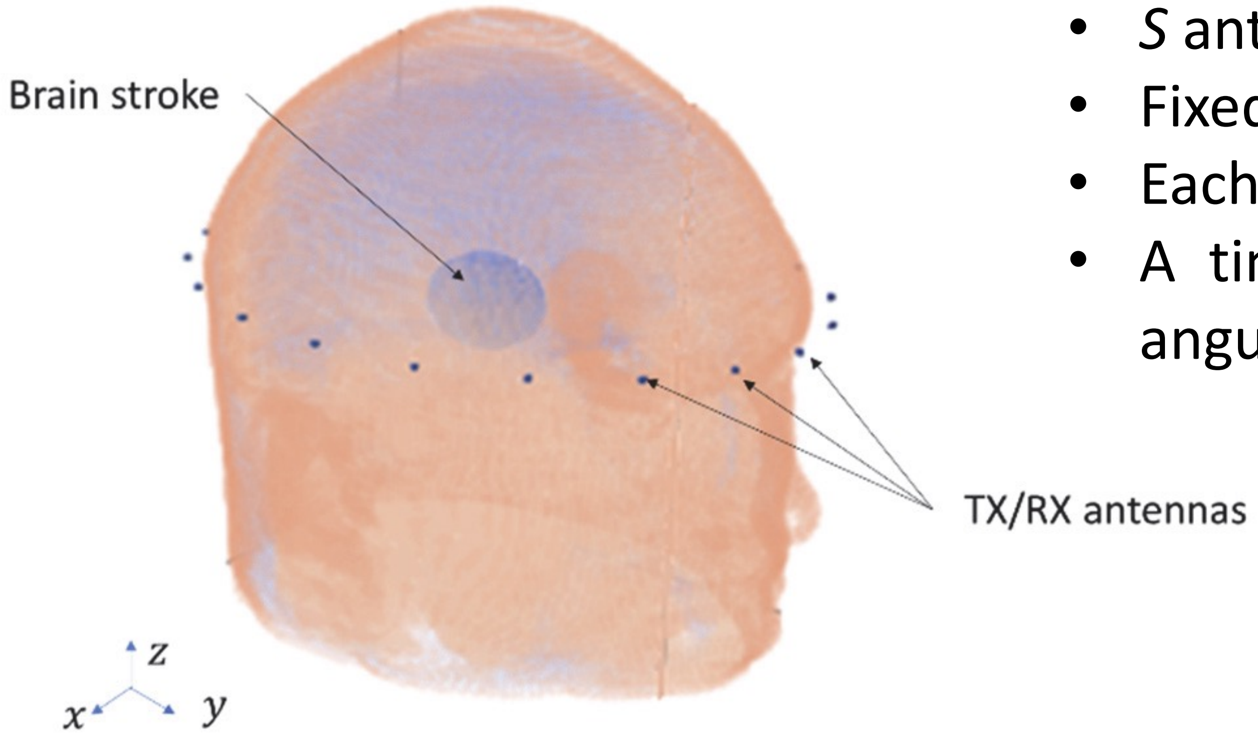
- Qualitative techniques relying on linearized scattering models or beamforming approaches;
- Quantitative methods based on iterative solution of full-non-linear scattering equations.

Machine learning-based methods have also been used to identify different kinds of brain strokes.

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Mathematical modeling*



- S antennas around the head;
- Fixed positions $\boldsymbol{r}_s$, s = 1, 2 … S;
- Each antenna generates an incident field $\boldsymbol{E}_b$;
- A time-harmonic electromagnetic radiation with angular frequency ω is assumed.

The total field resulting from the interaction between the incident radiation and the head is collected by the other S-1 antennas.

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Mathematical modeling*

The total field due to the *s*-th antenna, at the *m*-th measuring point, is given by:

$$\mathbf{E}(\mathbf{r}_m,\omega) = \mathbf{E}_b(\mathbf{r}_m,\omega) - k_b^2 \int_V \chi(\mathbf{r}',\omega)\,\mathbf{E}(\mathbf{r}',\omega)\cdot\bar{\mathbf{G}}_b(\mathbf{r}_m,\mathbf{r}',\omega)d\mathbf{r}'$$

- Wavenumber in the external medium k_b
- Dyadic Green's function in the background $\bar{\mathbf{G}}_b$

Whereas the contrast function is given by:

$$\chi(\mathbf{r},\omega) = \frac{\varepsilon(\mathbf{r},\omega)}{\varepsilon_b(\mathbf{r},\omega)} - 1$$

- Complex dielectric permittivity of the head ε
- Background complex dielectric permittivity ε_b

Note that $\mathbf{E}(\mathbf{r}_m,\omega)$ is non-linear with χ.

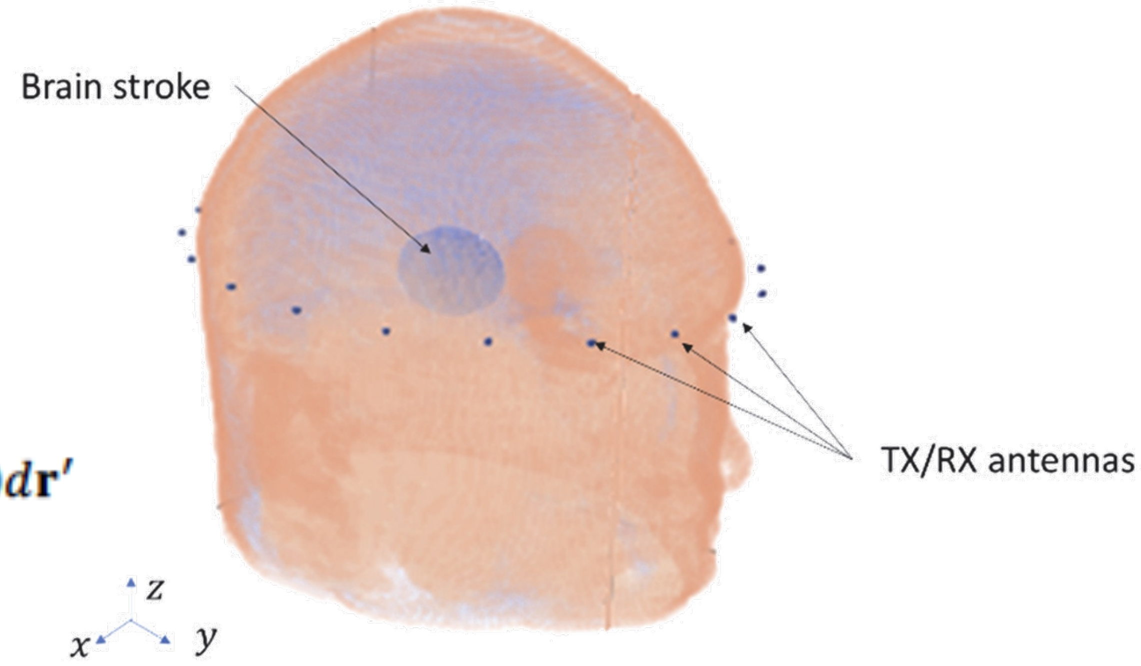
EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Mathematical modeling*

If coplanar antennas are used, i. e., if they are located all at the same height, assuming a TM-z polarized incident field and neglecting the spatial variation along the z-axis, the scattering equation reduces to the following 2D scalar equation:

$$E_z(\mathbf{r}_m,\omega) = E_{z,b}(\mathbf{r}_m,\omega) - k_b^2 \int_D \chi(\mathbf{r}',\omega)\, E_z(\mathbf{r}',\omega) g_b(\mathbf{r}_m,\mathbf{r}',\omega) d\mathbf{r}'$$



Where g_b is the 2D Green's function.

Showcase: brain stroke

✓ *Working conditions*

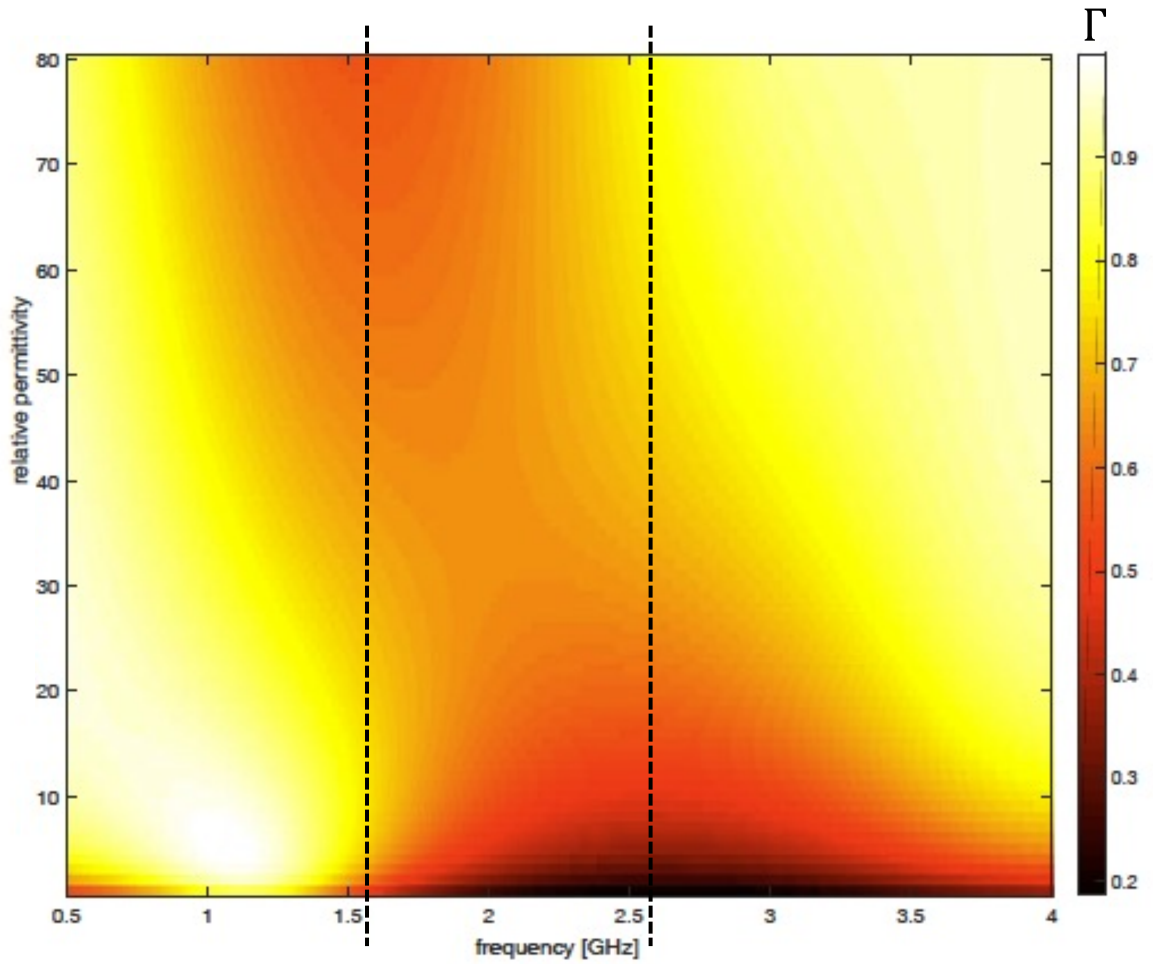
Two key parameters must be set for the MWI system that play a crucial role by affecting other design choices (e. g., the kind of antennas to be used):

- The frequency band
- The coupling medium in which antennas are hosted (i. e., the background medium)

Their selection aims at maximizing the fraction of incident power that penetrates into the head and its penetration depth, as well as to allow the detection of as small as possible variations (satisfactory spatial resolution). As a matter of fact, these requirements are affected by the wavelength in the host medium, which is in turn due to the adopted frequency band and coupling medium.

EM fields for biomedical diagnostics

Showcase: brain stroke



✓ *Working conditions*

- To mimic the head, a simple planar layered model to study the transmission of the incident plane wave can be used.
- The average thickness of the various tissue layers present in the head is considered.
- Forbidden zone: frequency range at which a total reflection occurs due to the 3-layer structure high permittivity – low permittivity (skull) – high permittivity.

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Qualitative imaging*

- Although computational efforts needed to solve non-linear and ill-posed inverse scattering problems are not suitable for real-time brain monitoring, simpler while yet effective MWI tools based on an approximated formulation of the scattering process would be very useful for the post-stroke monitoring.

- Such qualitative MWI comes from the fact that, typically, the goal is to detect small variations occurring in the part of the brain hit by stroke once information on the scattering scenario is already provided by the images of the patient taken at the time of the first diagnosis.

- This results in a linear and ill-posed approximated problem, which is free from false solutions and can be handled using reliable and effective inversion strategies, i. e., regularization algorithsm as the Truncated Singular Value Decomposition and Tikhonov's one.

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Qualitative imaging*

The core of the linear model is the Born approximation, according to which the total electric field $\mathbf{E}(\mathbf{r}', \omega)$ inside the region under test can be approximated with the incident radiation therein computed, given the weak perturbation induced by the target:

$$\mathbf{E}(\mathbf{r}_m, \omega) = \mathbf{E}_b(\mathbf{r}_m, \omega) - k_b^2 \int_V \chi(\mathbf{r}', \omega)\, \mathbf{E}_b(\mathbf{r}', \omega) \cdot \overline{\mathbf{G}}_b(\mathbf{r}_m, \mathbf{r}', \omega) d\mathbf{r}'.$$

the data to unknown relationship follows by considering the differential scattered field $\Delta\boldsymbol{E}_S$:

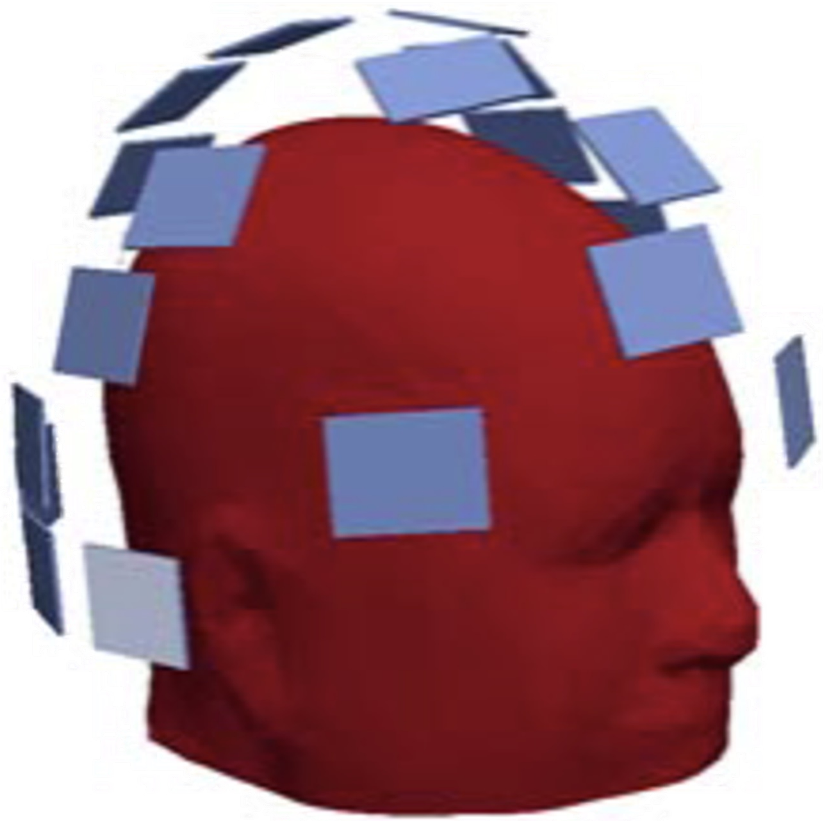
$$\Delta\mathbf{E}_s(\mathbf{r}_m, \omega) = k_b^2 \int_V \Delta\chi(\mathbf{r}', \omega)\, \mathbf{E}_b(\mathbf{r}', \omega) \cdot \overline{\mathbf{G}}_b(\mathbf{r}_m, \mathbf{r}', \omega) d\mathbf{r}'$$

- Differential contrast function enconding the evolution of the disease $\Delta\chi$

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Qualitative imaging*



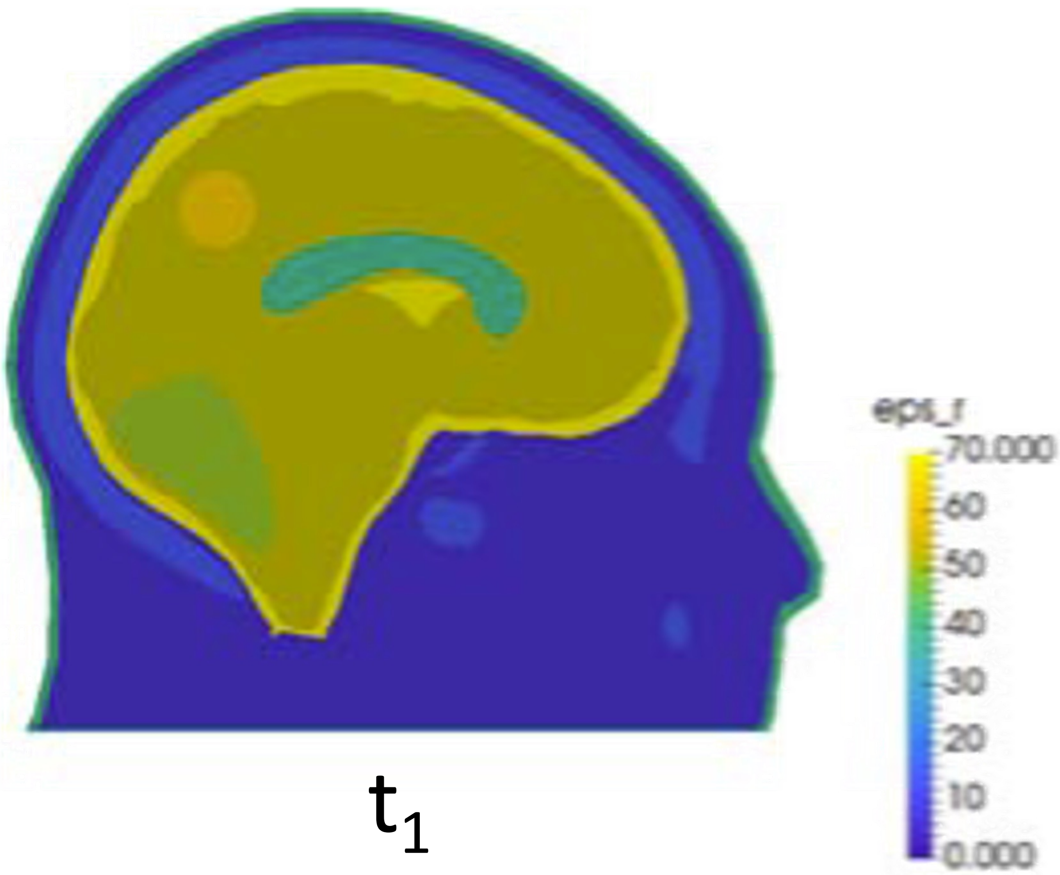
Realistic 3D case:

- Realistic monopole antennas (24) configuration
- Matching liquid (Triton X-100 + water)
- Radius of the spherical blood target at time t_1, 1 cm
- Radius of the spherical blood target at time t_2, 2 cm
- Full-wave 3D Finite Element Method simulations
- $\boldsymbol{E}_b(\mathbf{r}', \omega)$ is calculated with an average value head, assuming the shape of the region is known
- Noise is artificially added before inputting the simulated data in the reconstruction algorithm

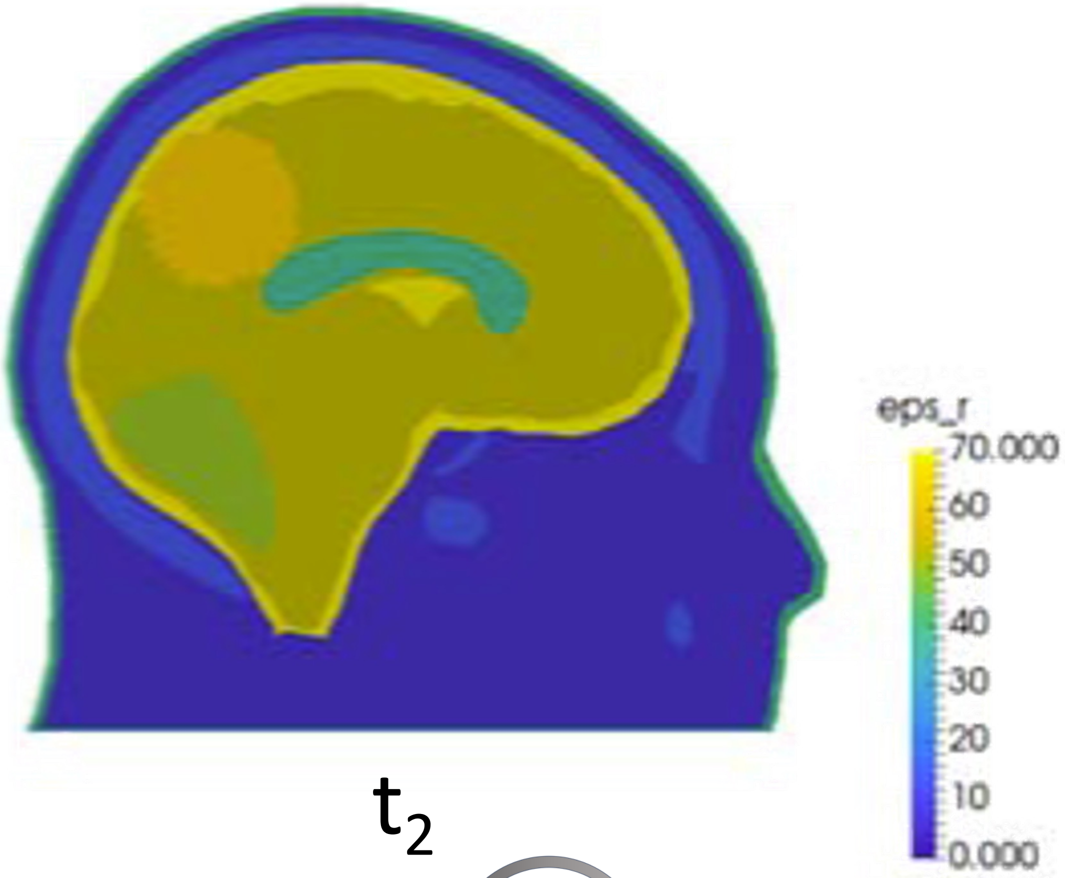
EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Qualitative imaging*



t_1

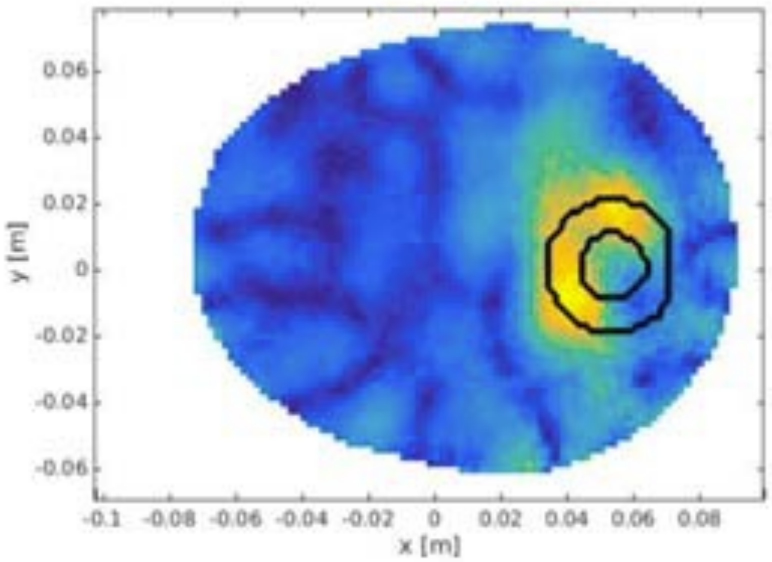


t_2

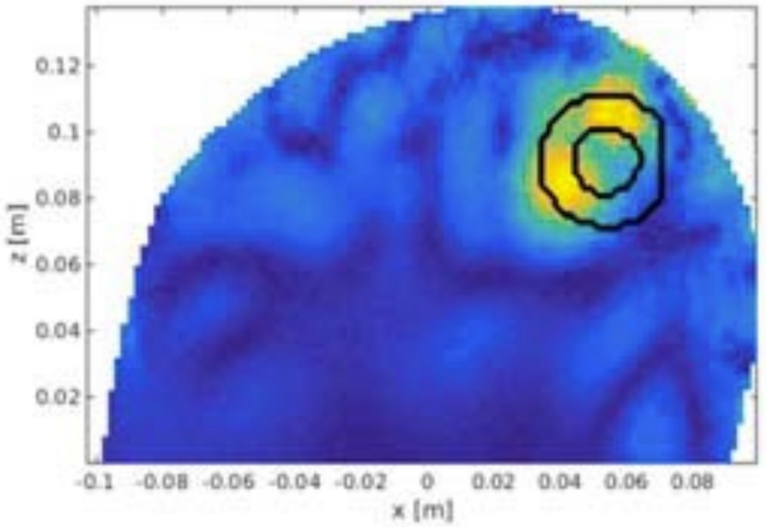
Showcase: brain stroke

✓ *Qualitative imaging*

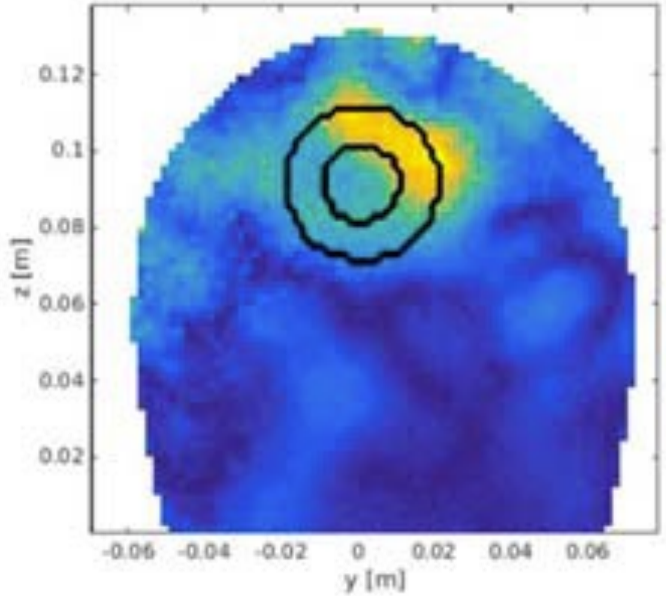
Reconstruction of the differential scattered field (SNR = 80 dB)



Transverse plane



Sagittal plane

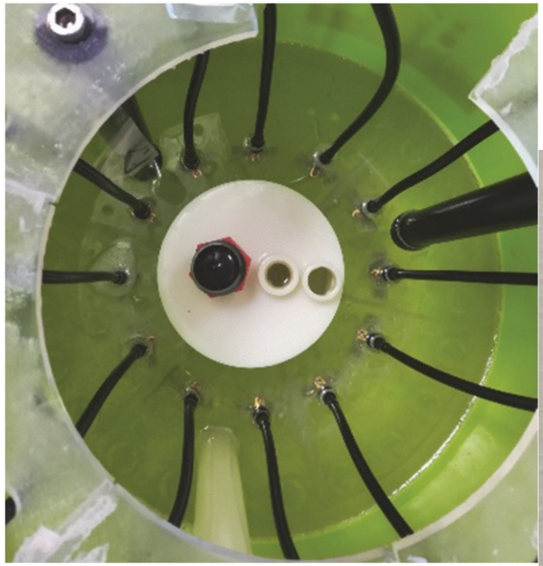


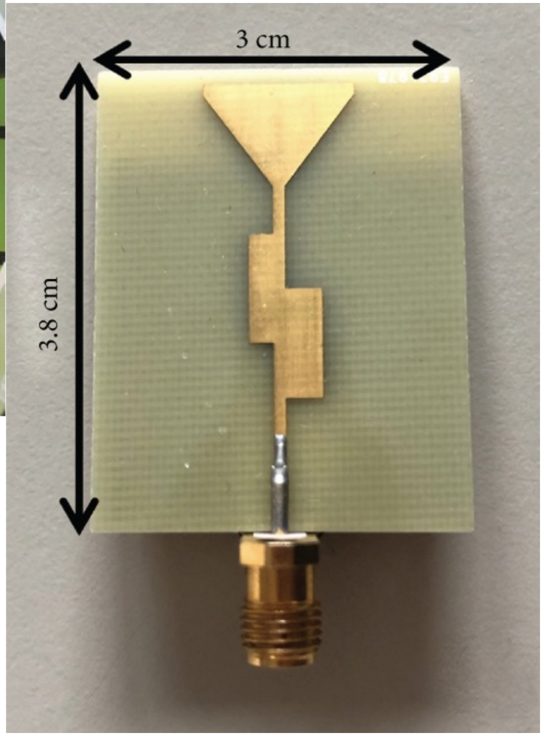
Frontal plane

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Qualitative imaging*





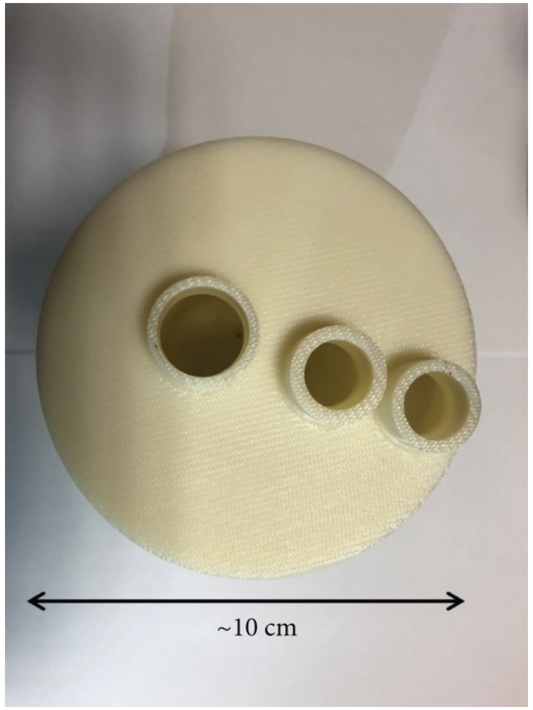
Experimental 2D case:

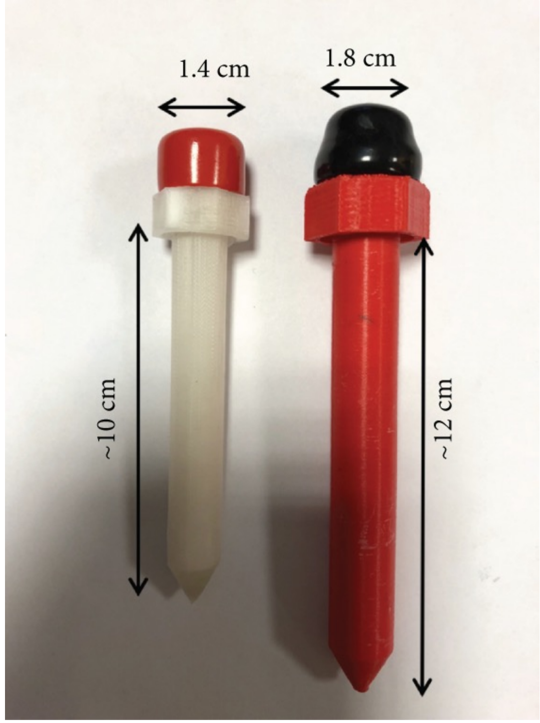
- Monopole antennas (12) configuration
- 3D-printed cylindrical phantom (filled with liquids mimicking a brain tissue)
- Coupling liquid: Triton X-100 (70%) + water (30%)
- Brain tissue (blend of 75% white and 25% grey matter)
- Small blood cylinder to simulate hemorrhagic stroke area
- Brain/blood mimicking liquids (TX100 + salty water mixture)
- PNA microwave Network Analyzer (1 GHz – 1.75 GHz)

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Qualitative imaging*





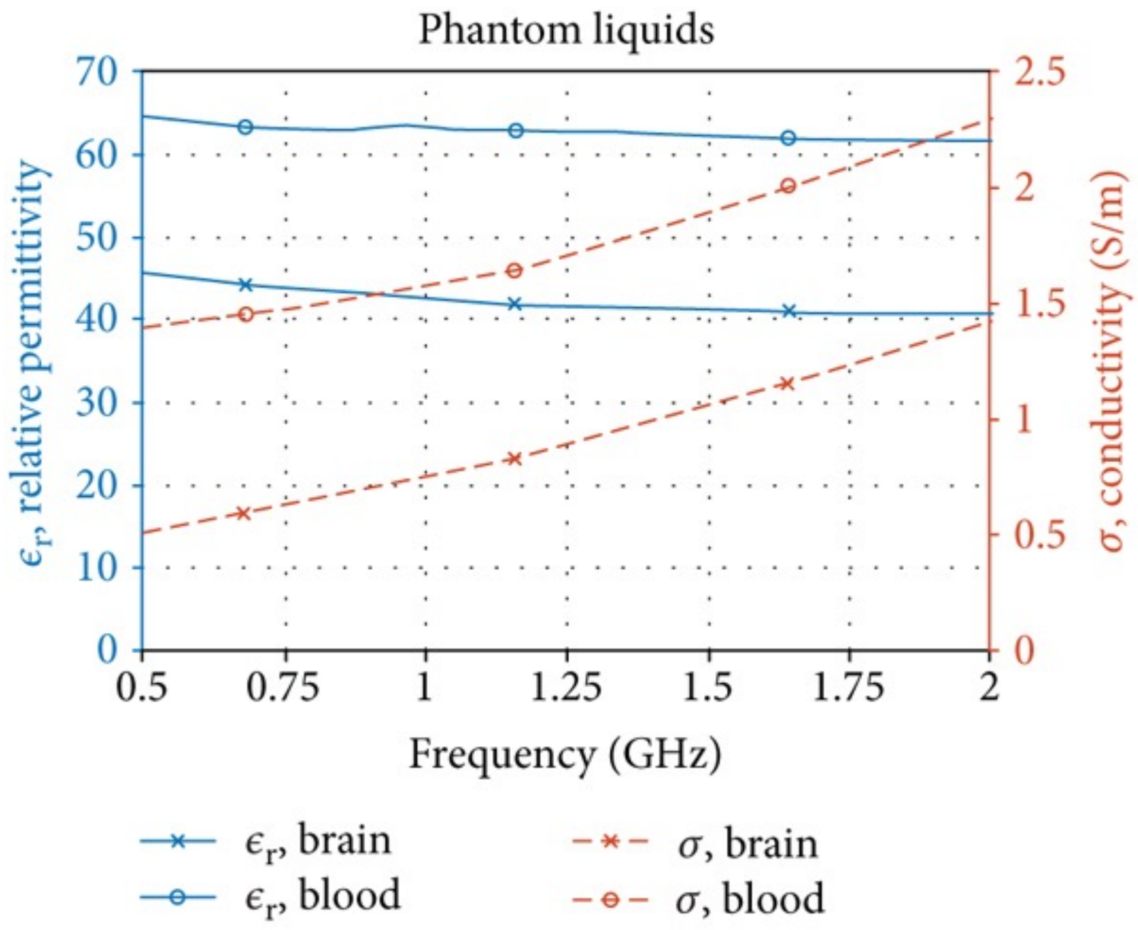
Experimental 2D case:

- Monopole antennas (12) configuration
- 3D-printed cylindrical phantom (filled with liquids mimicking a brain tissue)
- Coupling liquid: Triton X-100 (70%) + water (30%)
- Brain tissue (blend of 75% white and 25% grey matter)
- Small blood cylinder to simulate hemorrhagic stroke area
- Brain/blood mimicking liquids (TX100 + salty water mixture)
- PNA microwave Network Analyzer (1 GHz – 1.75 GHz)

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Qualitative imaging*



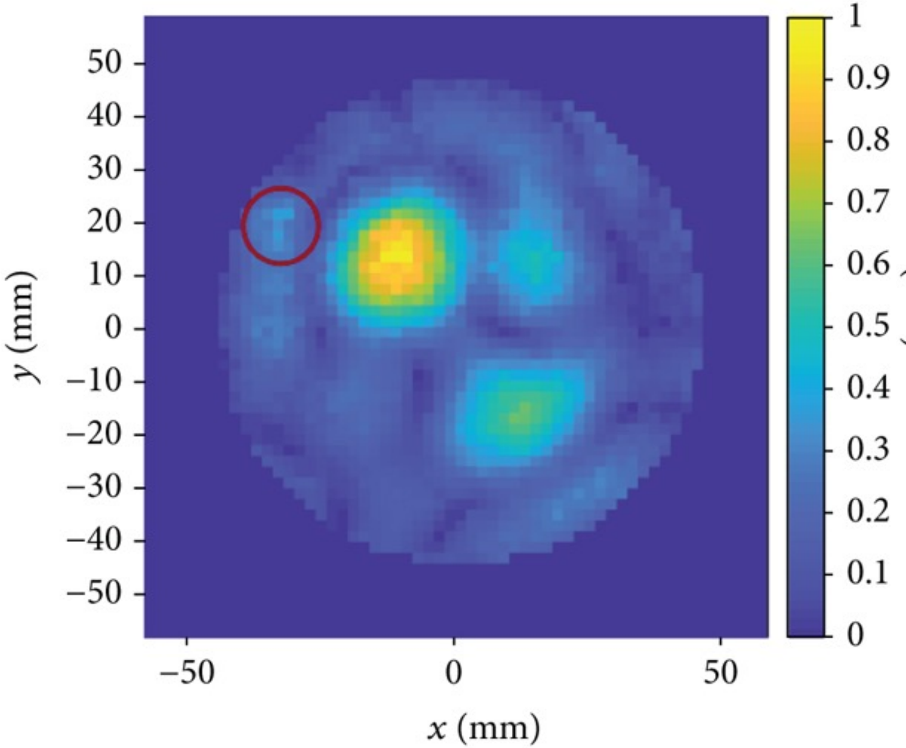
Dielectric properties of the tissue-mimicking mixtures measured by means of an open-ended coaxial probe connected to the PNA Network Analyzer in the 0.5 – 2 GHz operating frequency range.

EM fields for biomedical diagnostics

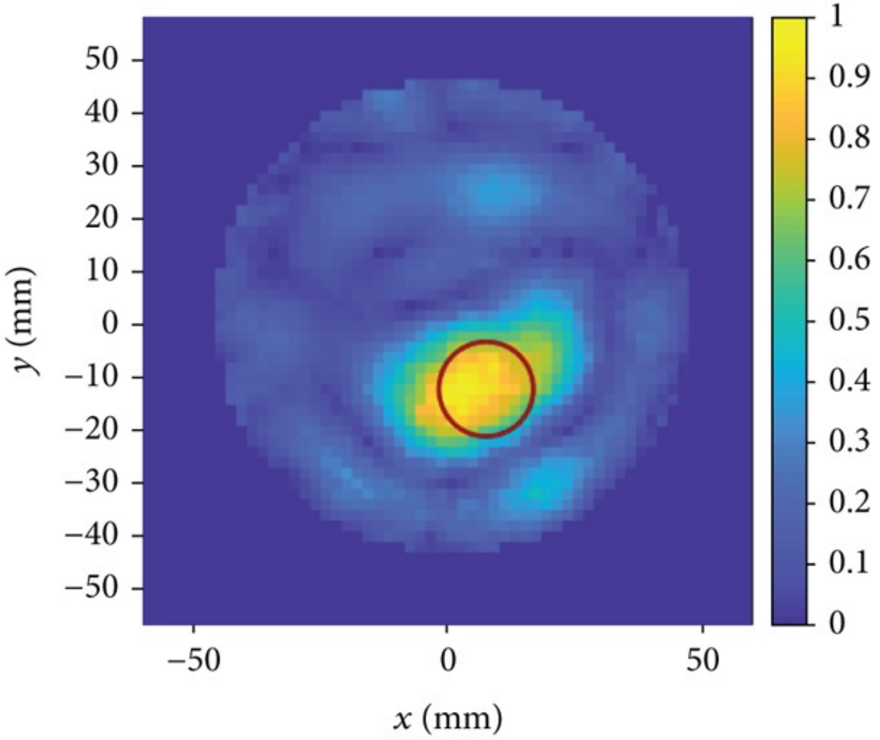
Showcase: brain stroke

✓ *Qualitative imaging*

Reconstruction of the differential scattered field (phantom with and without target)



Small boundary target (1.4 cm cylinder)



Large centered target (1.8 cm cylinder)

Metric	Left	Right
Dimensional error	1.39	1.41
Localization error (mm)	38.0	0.5
Side lobe Level (dB)	-4.4	-8.4

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Quantitative imaging*

When linearized models cannot be adopted, e. g., when a suitable model of the healthy head is not available, it is necessary to address the full non-linear problem. The case of simplified 2D model is considered in the following. Similar relationships can be however obtained also when considering the full 3D problem.

The 2D scalar scattering equation (co-planar antennas case) can be compacted as:

$$\Delta E_z(\mathbf{r},\omega) = \mathcal{G}_{obs}\chi(I - \mathcal{G}_{inv}\chi)^{-1}E_{z,b}(\mathbf{r},\omega) = \mathcal{F}(\chi)(\mathbf{r}), \quad \mathbf{r} \in D_{obs}$$

$$\mathcal{G}_{inv/obs} f(\mathbf{r}) = -k_b^2 \int_D f(\mathbf{r}')g_b(\mathbf{r},\mathbf{r}')d\mathbf{r}', \mathbf{r} \in D/D_{obs}$$

- $\Delta E_z(\mathbf{r},\omega) = E_z(\mathbf{r},\omega) - E_{z,b}(\mathbf{r},\omega)$
- Spatial domain where measurements (the set of points $\mathbf{r}_m$ is available) D_{obs}
- Linear operators $\mathcal{G}_{obs}$, $\mathcal{G}_{inv}$

EM fields for biomedical diagnostics

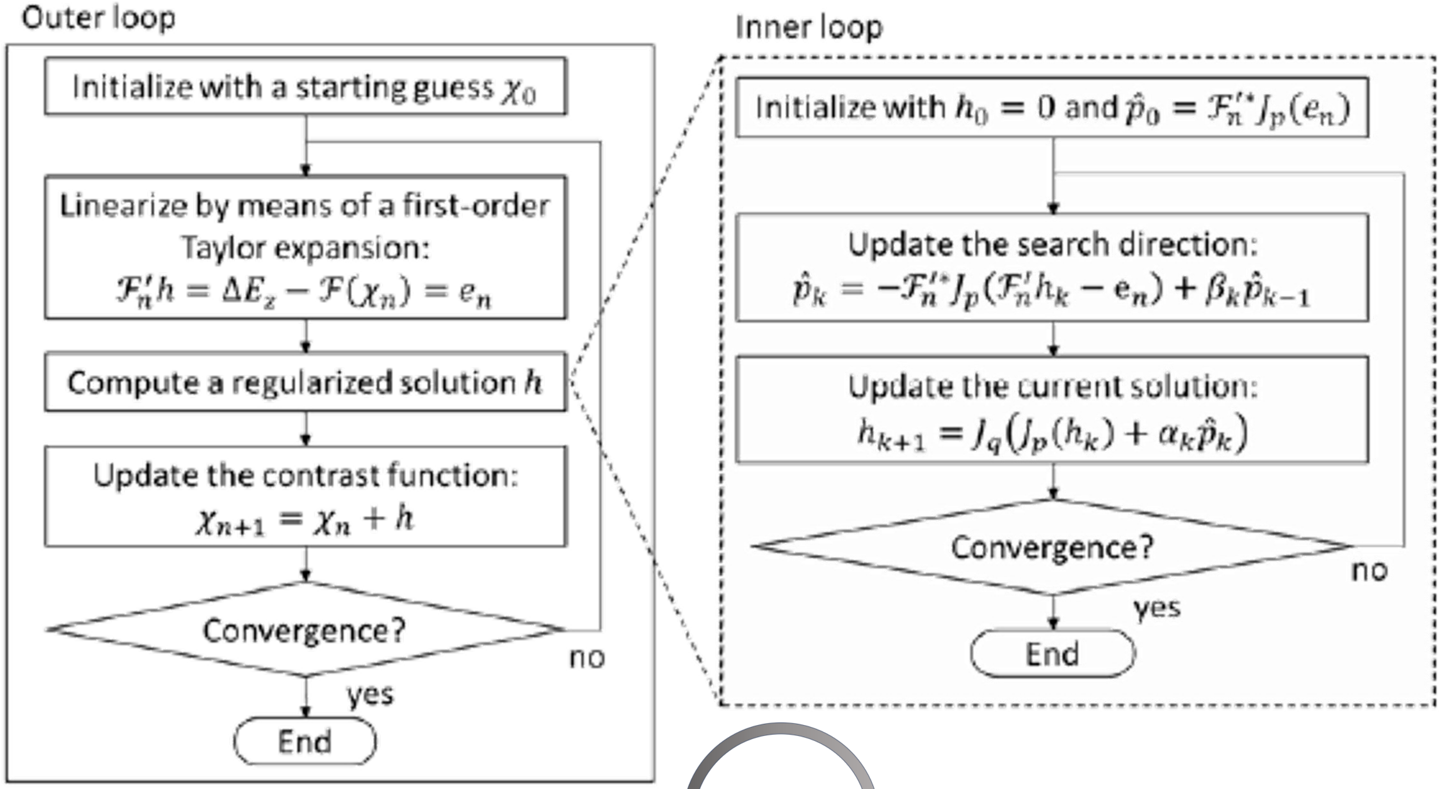
Showcase: brain stroke

✓ *Quantitative imaging*

The differential field $\Delta E_z(\mathbf{r}, \omega)$ needs to be inverted in order to retrieve the contrast function from the available scattered-field measurements. Being the inverse problem:

- Non-linear
- Strongly ill-posed

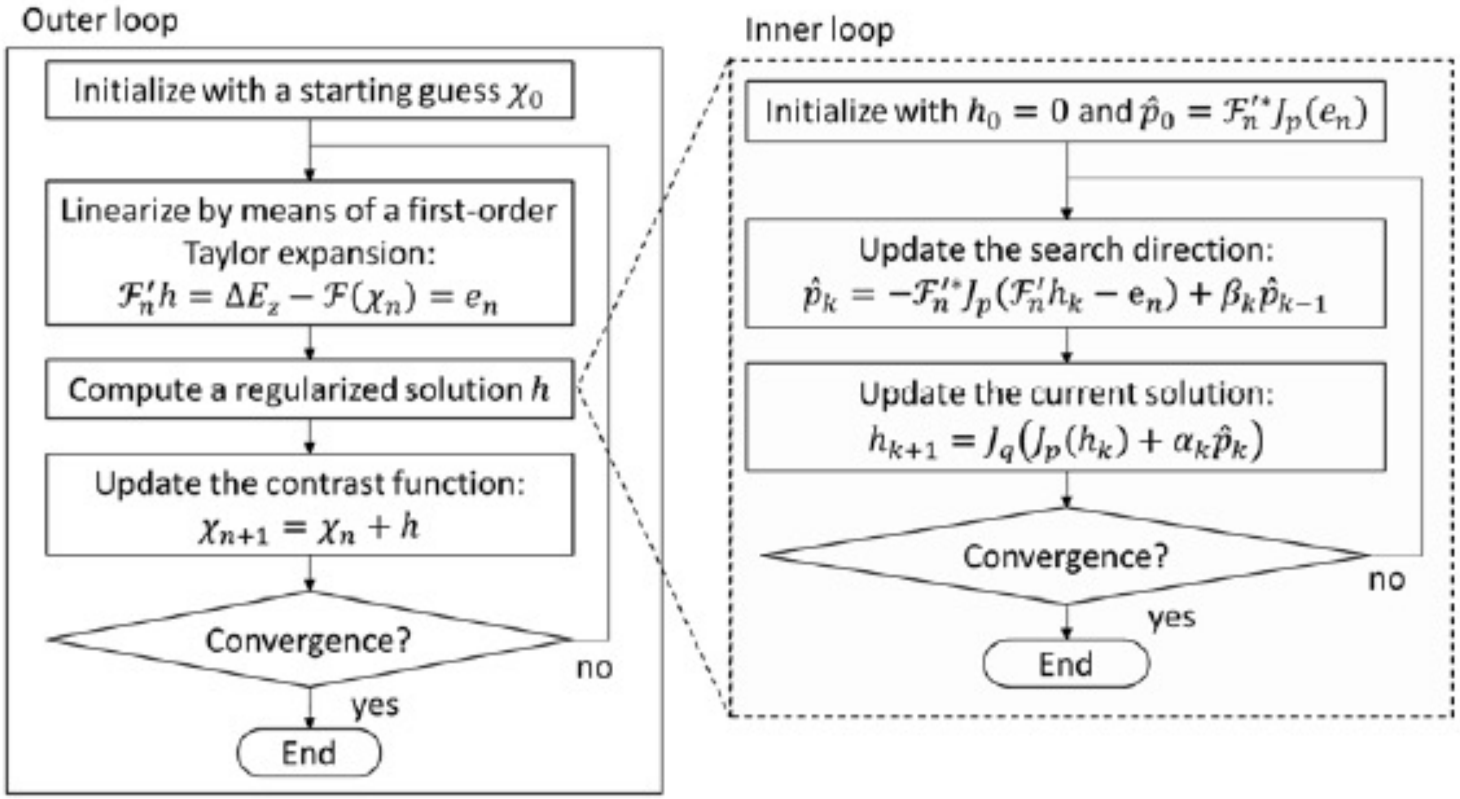
Non-linear regularization algorithms should be adopted as the Lebesgue-space inversion procedure based on a two nested loop Newton scheme with a conjugate-gradient-like inner solver.



EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Quantitative imaging*



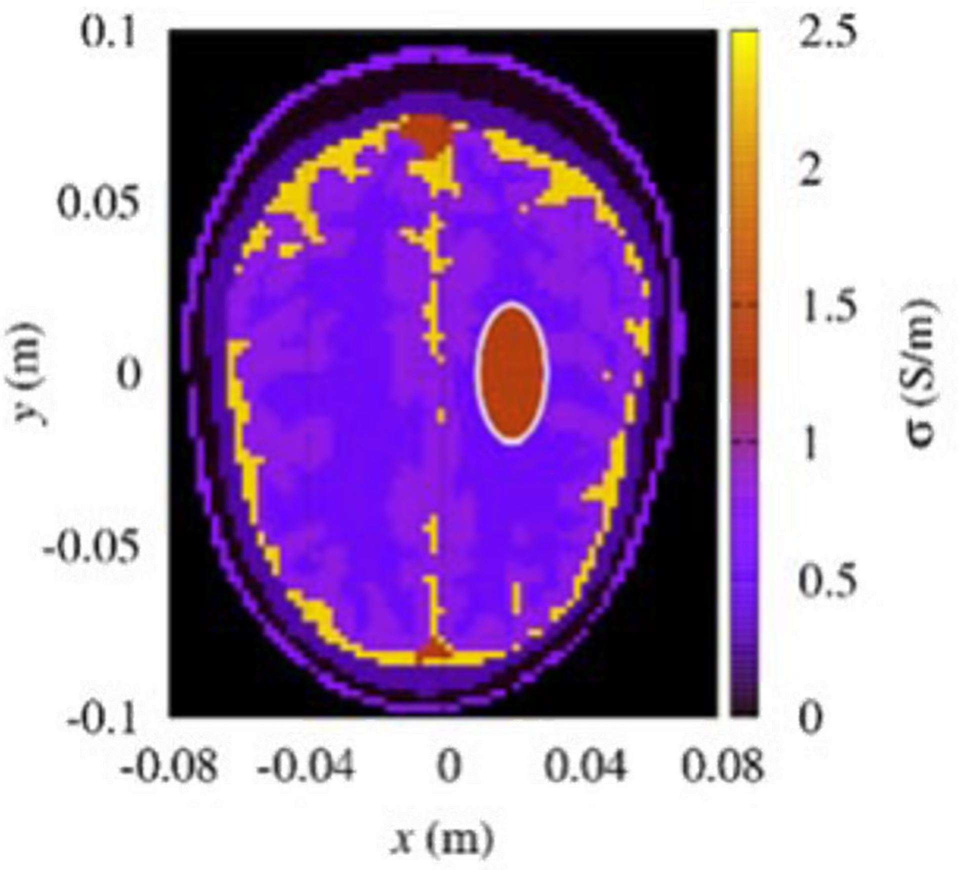
- Outer loop: iterative linearization of the non-linear operator $\mathcal{F}$ by means of a first-order Taylor expansion around the current estimate of the solution.
- Inner loop: solution of the linearized problem using a conjugate-gradient algorithm, which performs a regularization in the framework of the Lebesgue spaces L^p, with $p > 1$.

It is worth noting that p represents a new hyperparameter to be tuned in order to enhance the reconstruction performance. It has empirically found that $p < 2$ allows obtaining reconstruction characterized by lower oversmoothing and ringing effects than the conventional Hilbert-space conjugate-gradient procedure.

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Quantitative imaging*



Actual configuration

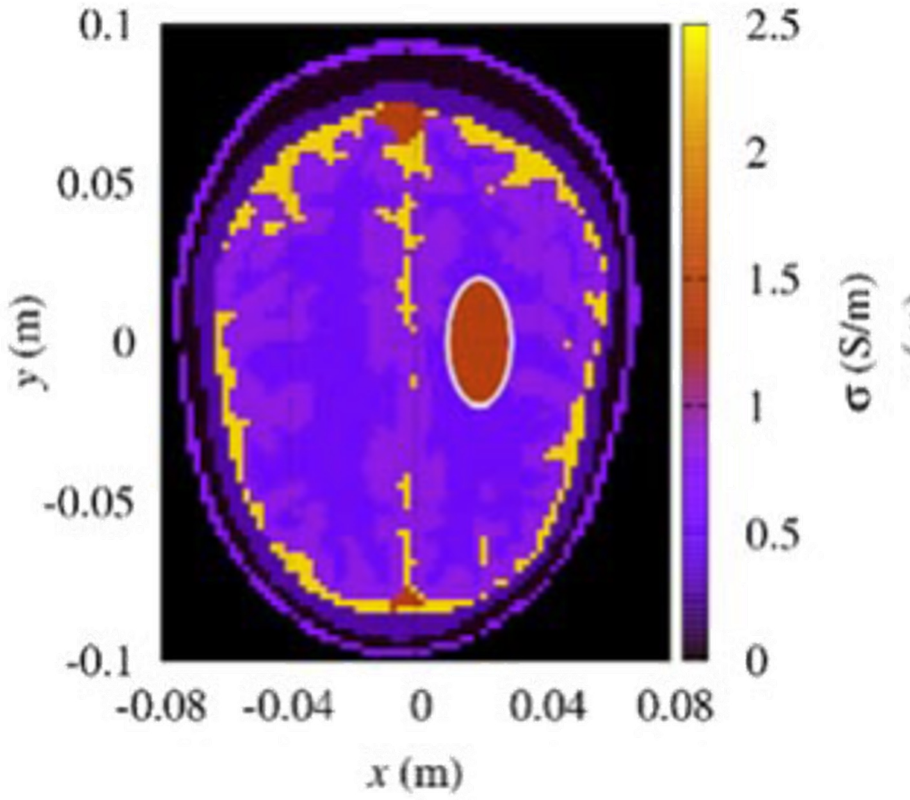
Numerical analysis:

- Slice of Zubal head model (d_z= 5.46 cm far from the top of the head)
- Dielectric properties of the tissues described by the Cole-Cole model
- Coupling medium: Glycerin (70%) + water (30%) mixture
- Stroke modelled as elliptical bloody target (semi-axes: 2/4 cm long)
- Homogeneous head (white matter)
- Elliptical investigation domain (semi-axes: 16/20 cm long)
- *S* = 30 external linear antennas
- Working frequency: 600 MHz
- Solver: MoM (5199 mesh square grid, domain)
- Solver: MoM (1300 mesh square grid, head)
- Additive 0-mean Gaussian noise (SNR = 25 dB)

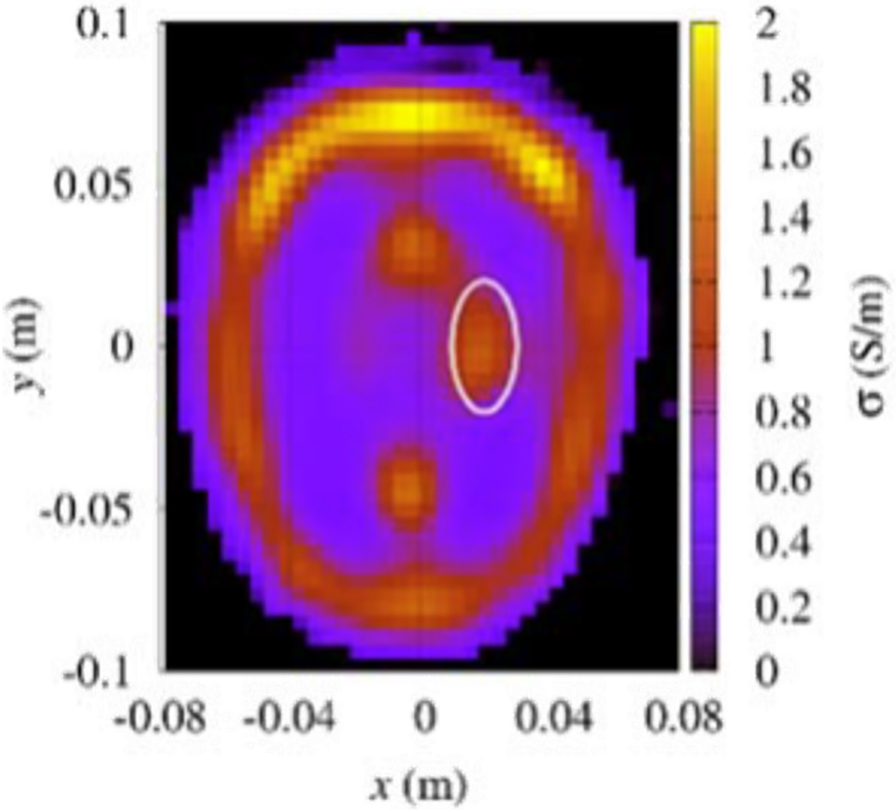
EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Quantitative imaging*



Actual configuration

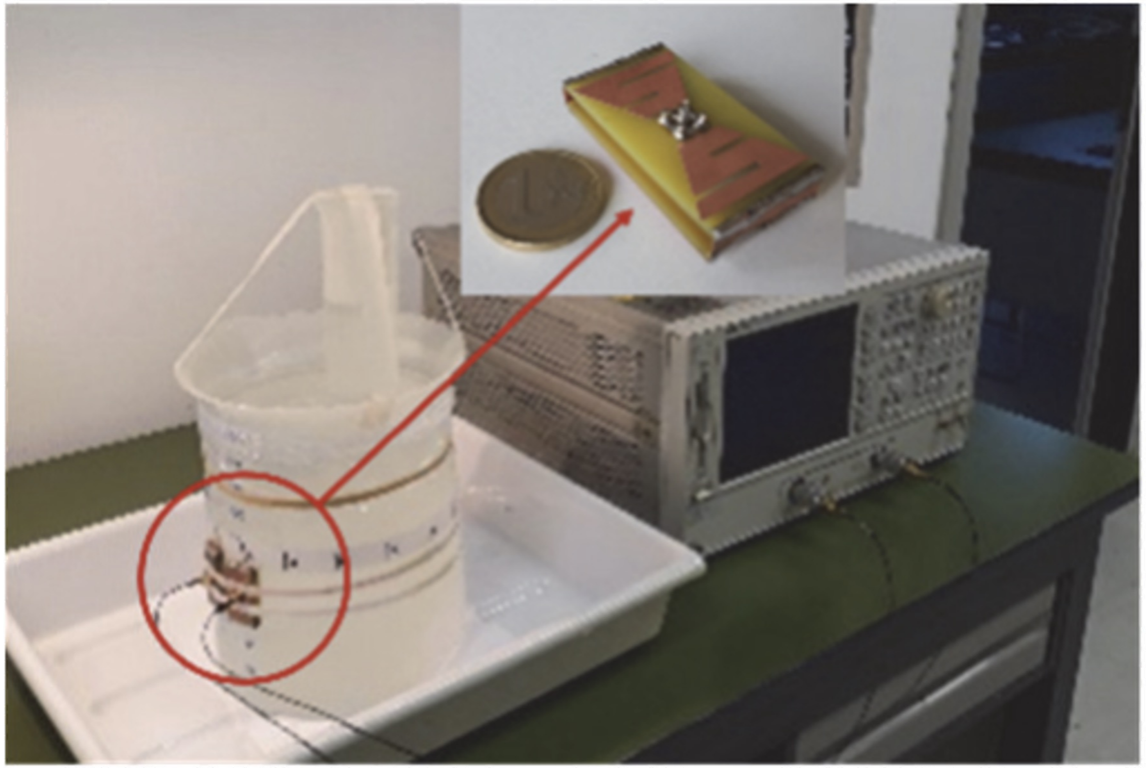


Reconstructed σ distribution (p = 1.3)

EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Quantitative imaging*



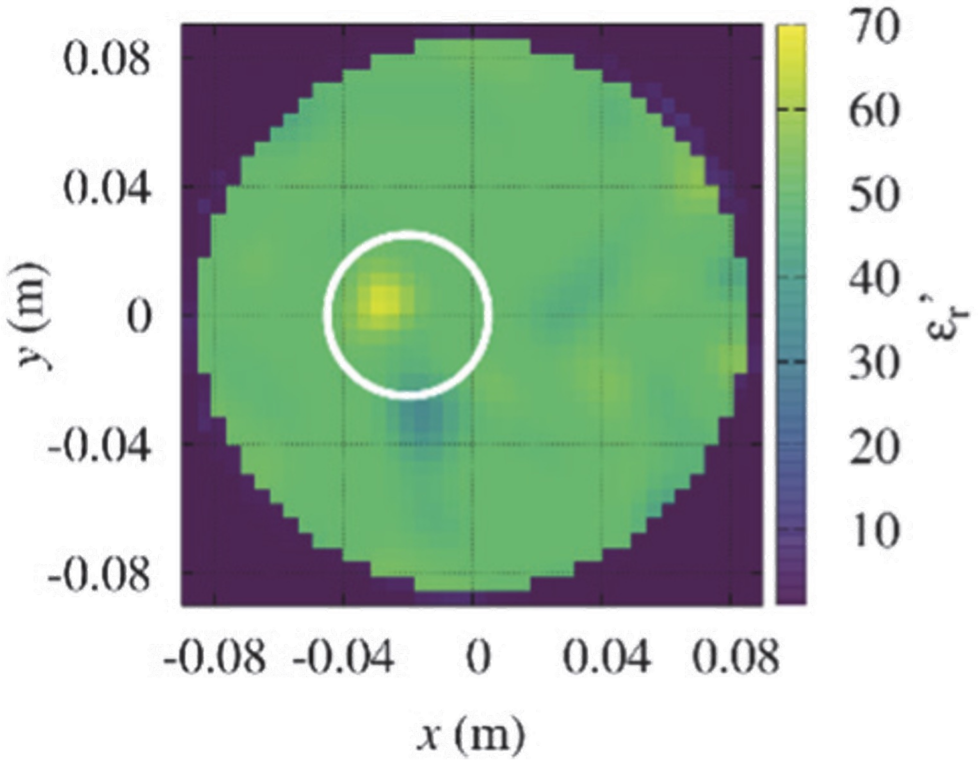
Experimental analysis:

- Cavity-backed slotted bowtie equi-spaced contact antennas
- Vector Network Analyzer
- Multi-static configuration (*S* = 16 positions)
- Working frequency: 600 MHz
- Simplified phantom (5 L cylindrical polypropylene beaker whose external diameter is 180 mm and wall thickness is 4 mm, filled with a glycerin/water mixture $\varepsilon_r = 50 - j24$)
- Stroke simulated with a cylindrical inclusion (500 mL polypropylene circular cylinder whose diameter is 52 mm) filled with a different glycerin/water mixture ($\varepsilon_r = 60 - j11$)
- Coupling medium: Glycerin (70%) + water (30%) mixture
- Domain: 1264 mesh square grid

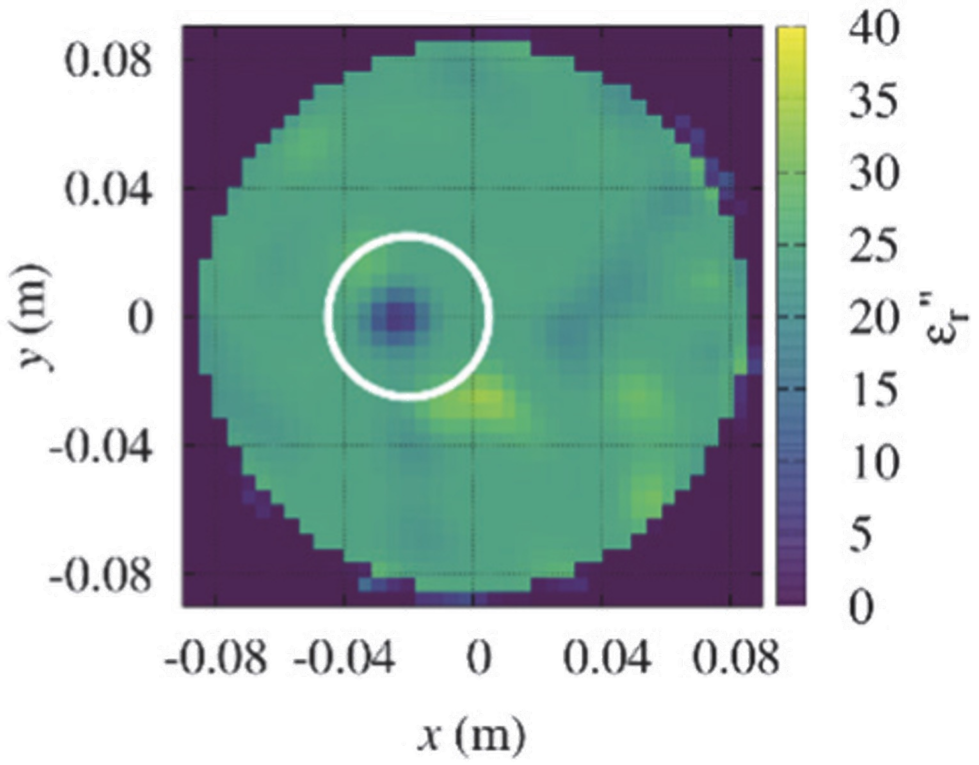
EM fields for biomedical diagnostics

Showcase: brain stroke

✓ *Quantitative imaging*



Reconstructed map of the
relative dielectric permittivity (p = 1.2)



Reconstructed map of the
electric conductivity (p = 1.2)

EM fields for biomedical diagnostics

Showcase: brain stroke

Final remarks:

- MWI methods are emerging as potential tools for brain stroke detection and monitoring.
- Both qualitative and quantitative inverse scattering approaches can be applied to brain stroke detection.
- A qualitative approach is suitable to monitor the brain stroke evolution, while a quantitative technique is needed to identify and characterize the stroke-affected tissues.
- For both methods, numerical simulations and prototype experimental setups are available.