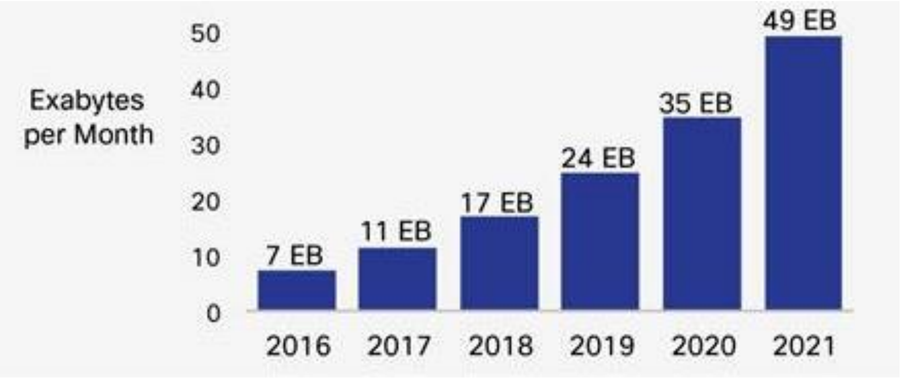
Evaluation d’exposition du vivant en ondes millimétriques dans les scénarios 5G

MAXIM ZHADOBOV

Centre national de la recherche scientifique

Nearly twofold increase in mobile traffic is expected by 2021



Cisco data traffic evolution forecast

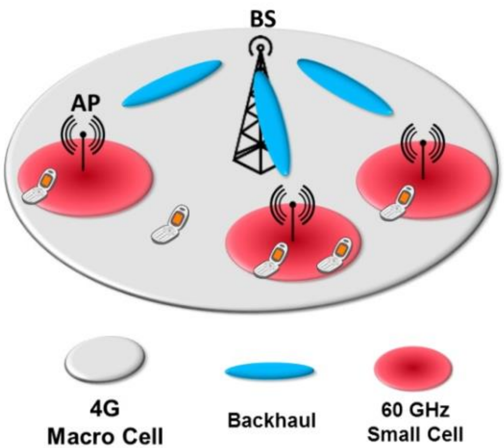
Shifting towards the millimeter-wave band

Advantages of the 60-GHz band

- ✓ 9 GHz of unlicensed bandwidth
- ✓ Very high data rates (up to 5-7 Gb/s)
- ✓ Reduced size of wireless devices
- ✓ High level of security and low interference with adjacent networks

IETR / WAVES Team / BioMedical Electromagnetics

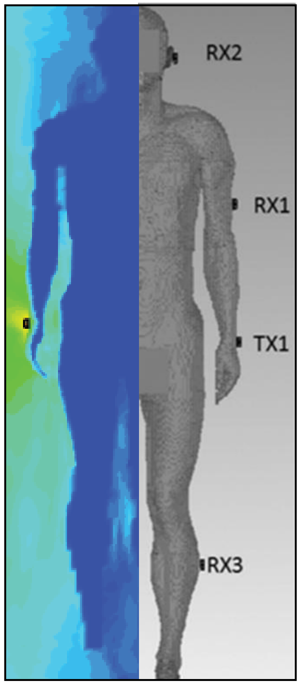
Dosimetry for 5G at mmW



5G HetNet topology

Representative use cases

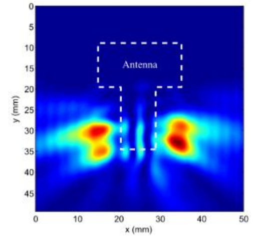
Body-centric wireless communications at mmW



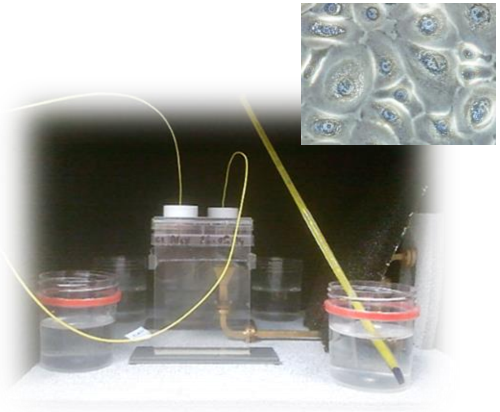
Antennas

Body models

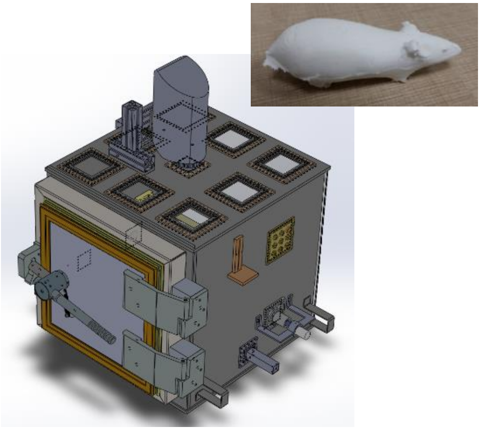
Dosimetry



Exposure systems for *in vitro* and *in vivo* studies



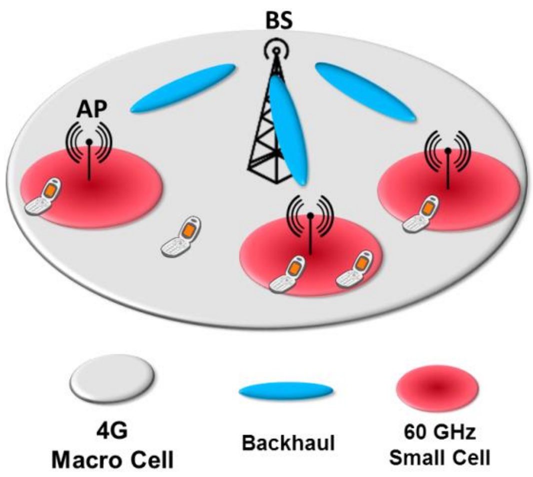
In vitro exposure at 60 GHz



Reverberation chamber for *in vivo* exposure at mmW

DOSIMETRY FOR 5G AT MMW

www.miwaves.eu



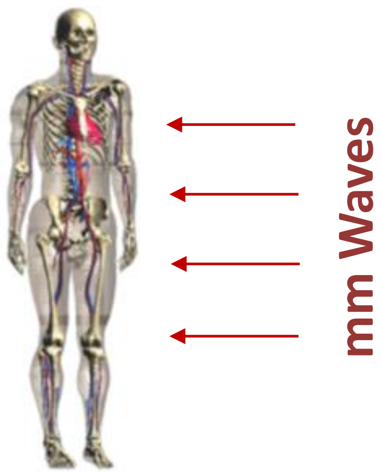
User exposure at mmW

Phone call

Browsing

Access point

INTERACTION OF MMW WITH THE HUMAN BODY



Penetration depth is shallow (@ 60 GHz δ ≈ 0.5 mm)

⬇

Absorption in the superficial layers

⬇

Primary biological targets are skin and cornea

- At 60 GHz, normal incidence, the **power transmission coefficient is around 60%** (and it increases with frequency).
- Shallow penetration depth of mmWs in skin induces **SAR levels significantly higher than those at microwaves** for identical IPD values (e.g. 100 W/kg for IPD = 1 mW/cm^2).
- **Clothing impacts the absorption in the body** (textile may increase the transmission, while an air gap between clothing and skin may reduce it).

M. Zhadobov, N. Chahat, R. Sauleau, C. Le Quement, Y. Le Dréan. Millimeter-wave interactions with the human body: state of knowledge and recent advances. *International Journal of Microwave and Wireless Technologies*, 3, pp. 237-247, 2011.

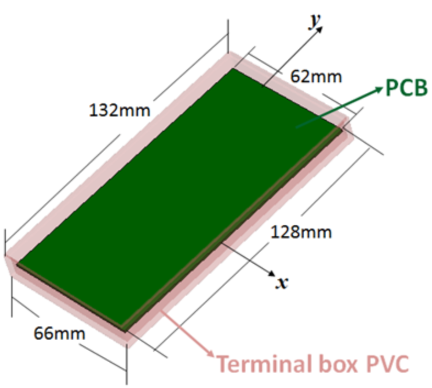
M. Zhadobov, C. Leduc, A. Guraliuc, N. Chahat, R. Sauleau. Antenna / human body interactions in the 60 GHz band: state of knowledge and recent advances. *State-of-the-Art in Body-Centric Wireless Communications and Associated Applications*, IET, 2016

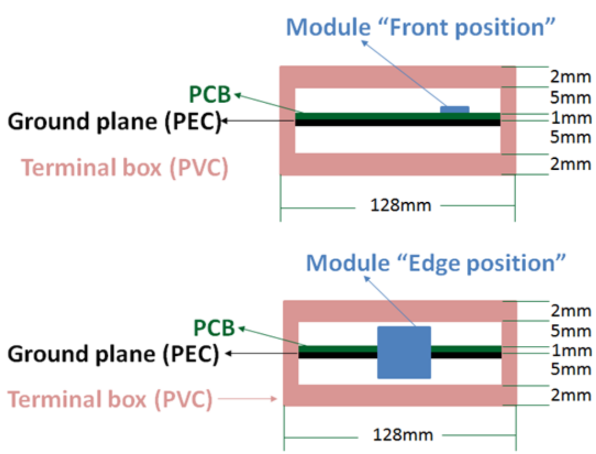
USAGE SCENARIOS & MOBILE USER TERMINAL

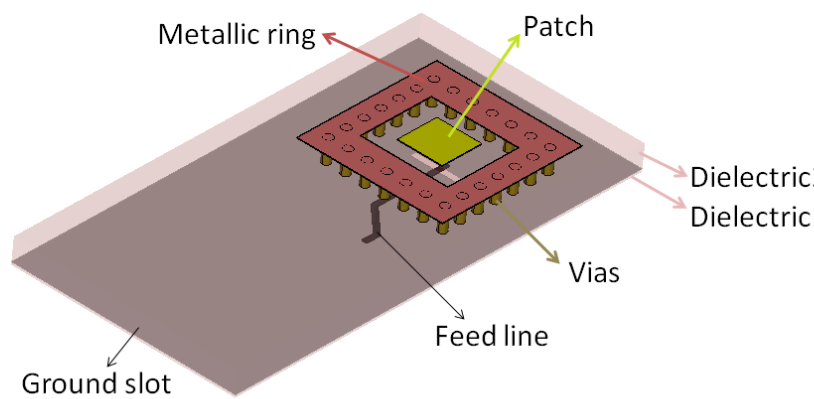
Phone call scenario

Front position | **Edge position**

Browsing scenario

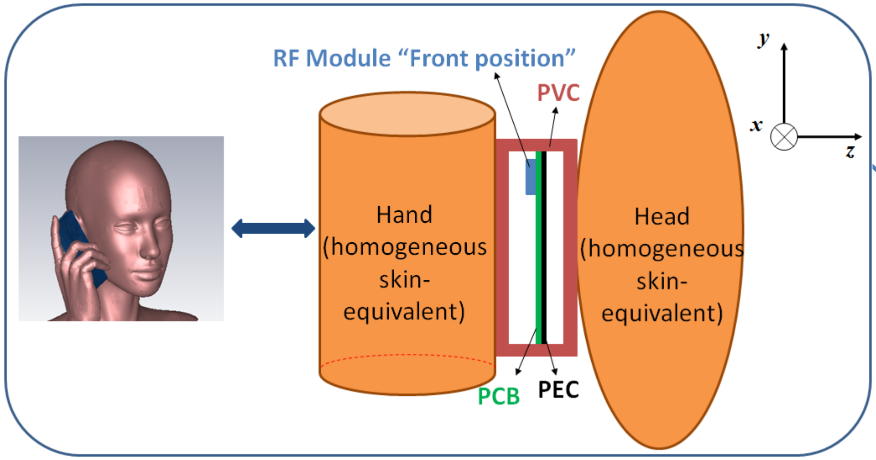


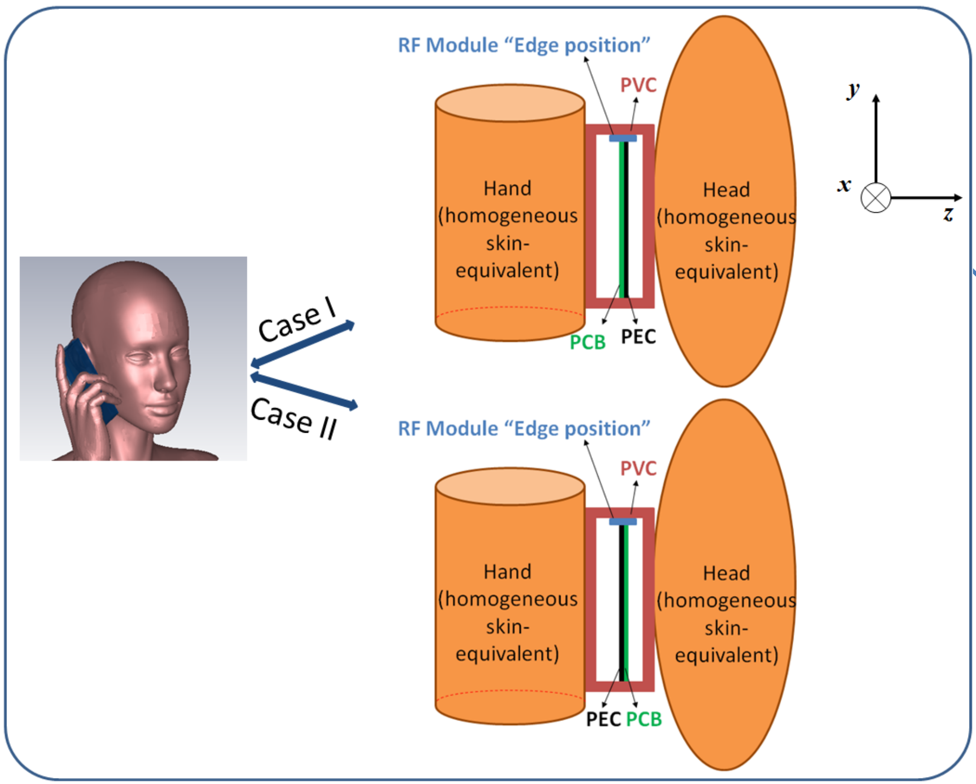


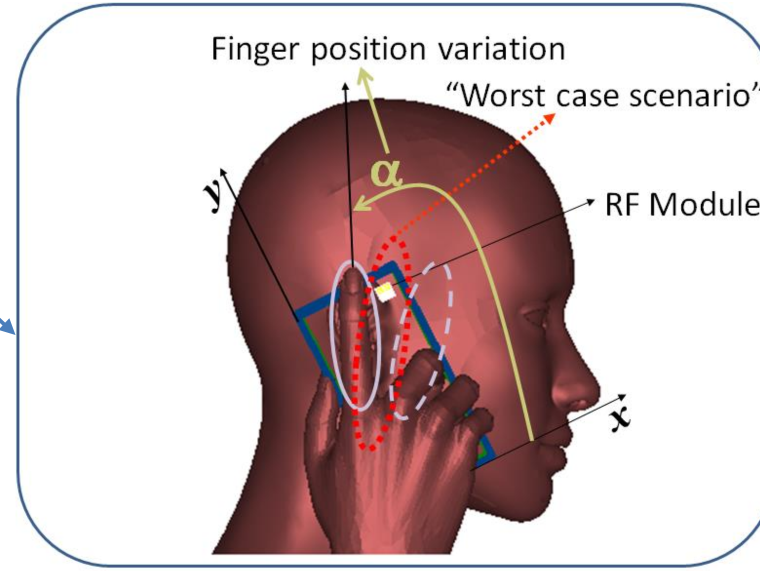


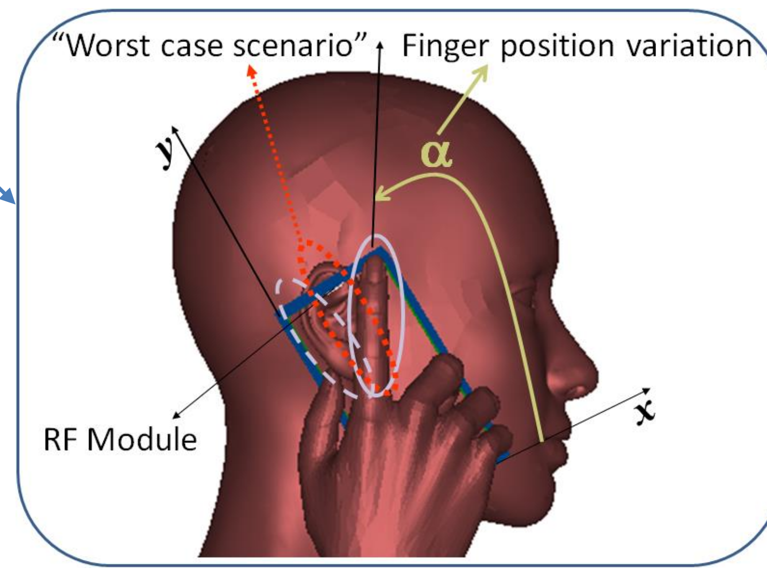
P = 10 mW

PHONE CALL SCENARIO

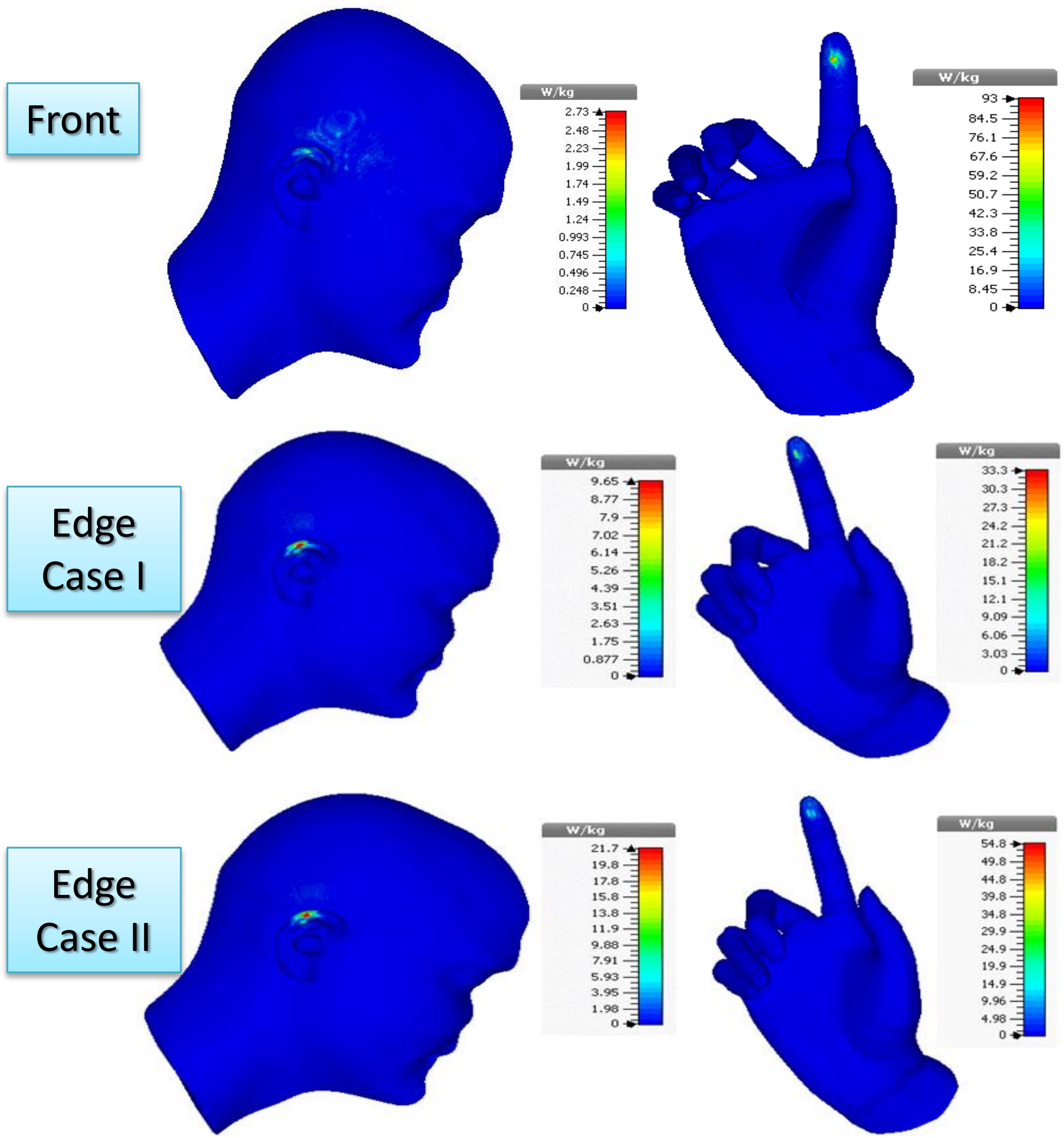








Phone call scenario – SAR



Maximum SAR occurs on the skin surface: user's ear and fingertips.

SAR locally distributed over a surface area of about 1 cm^2 on the hand and about 20 cm^2 on the head.

Metallic shield printed on the PCB towards the head increases the absorption in the hand.

Safety guidelines are set in terms of **Incident Power Density** (IPD)

	Frequency (GHz)	**Exposure type**	**IPD** (mW/cm^2)	**Averaging**		**Safety factor**
				Surface (cm^2)	**Time** (min)	
ICNIRP [1] (and CENELEC [2])	10-300	Occupational	5	20	$68/f^{1.05}$	
			100	1		
		General	1	20		
			20	1		
IEEE [3], [4]	30 - 300	Occupational	10	100	$2.524/f^{0.47}$	
	3 - 96		$200(f/3)^{0.2}$	1		
	> 96		400	1	$25.24/f^{0.47}$	
	30 - 100	General	1	100		
			20	1		
f – frequency in GHz						

Occupational

↓ ***F_S = 5 or 10***

General

[1] ICNIRP: "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)", Health Phys., vol. 74, no. 4, pp. 494-522, 1998.
[2] EN 50413 – 2008, "Basic standard on measurement and calculation procedures for human exposure to electric, magnetic and electromagnetic fields (0 Hz – 300 GHz)".
[3] IEEE Standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz, ISBN 0-7381-4835-0 SS95389, Apr. 2006.
[4] IEEE Standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz, ISBN 978-0-7381-6207-2 STD96039, Feb. 2010.

PHONE CALL SCENARIO – SUMMARY OF RESULTS

$$IPD_{eq}[W/m^2] = \frac{\rho\delta \cdot SAR(0)}{2 \cdot \left(1-|\Gamma|^2\right)}$$

<< ICNIRP recommended BRs
(1 mW/cm² over 20cm²; 20 mW/cm² over 1 cm²)

Antenna position	Absorption region	Absorbed power, mW	Peak SAR, W/kg	Peak IPD_{eq}, mW/cm²	Averaging			TRP, mW	Total efficiency, %
					SAR, W/kg	IPD, mW/cm²	Surface, cm²		
Front	Head	0.3	2.7	0.1	2.7×10^{-3}	0.1×10^{-3}	20	3.6	36
	Hand	4.1	93	3.9			1		
	Head (without the hand)	0.01	3.8×10^{-9}	1.6×10^{-10}	--	--	--	7.2	72
Edge – Case I	Head	0.6	9.7	0.4	0.9×10^{-3}	4×10^{-5}	20	3.1	31
	Hand	5.3	33.3	1.4	0.7×10^{-3}	3×10^{-5}	1		
	Head (without the hand)	0.07	5.4×10^{-8}	2.4×10^{-9}	--	--	--	7.8	78
Edge – Case II	Head	0.9	21.7	0.9	1.6×10^{-3}	7×10^{-5}	20	4.8	48
	Hand	3.4	55	2.3	1.1×10^{-3}	5×10^{-5}	1		
	Head (without the hand)	0.4	1.3×10^{-7}	0.6×10^{-8}	--	--	--	7.3	73

- Exposure levels are lower compared to the limits
- Presence of a hand increases the absorption in the head

Optimal position of the antenna module

✓ Edge position is an appropriate choice providing acceptable antenna performance and reduced use exposure.

✓ As far as the metallic shield printed on the PCB, both positions towards head or hand, can be chosen:

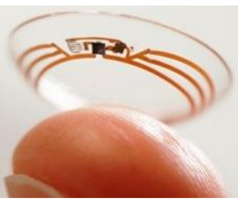
- PEC towards head – lower exposure (IPD_{eq_head} = 0.4 mW/cm^2, IPD_{eq_hand} = 1.4 mW/cm^2) lower antenna efficiency (31%)
- PEC towards hand – higher exposure (IPD_{eq_head} = 0.9 mW/cm^2, IPD_{eq_hand} = 2.3 mW/cm^2) higher antenna efficiency (48%)

A. Guraliuc, M. Zhadobov, R. Sauleau, L. Marnat, L. Dussopt. Near-field user exposure in forthcoming 5G scenarios in the 60-GHz band. *IEEE Transactions on Antennas and Propagation*, 65(12), pp. 6606-6615, Dec. 2017.

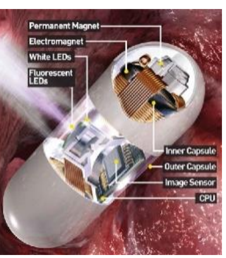
Body-centric wireless communications

Wireless networking between **sensors and communicating devices** placed on, off, or implanted in human body

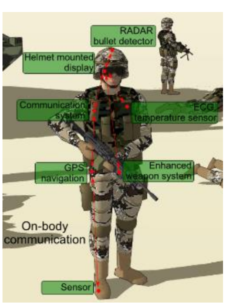
healthcare, sports, smart home, entertainment, military



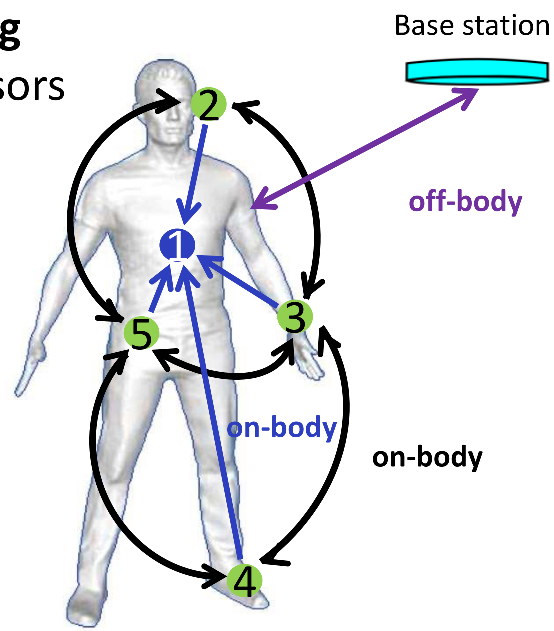
E-health monitoring
Smart wireless sensors



Wireless implants
Powering through the body



Person-to-person wireless communications

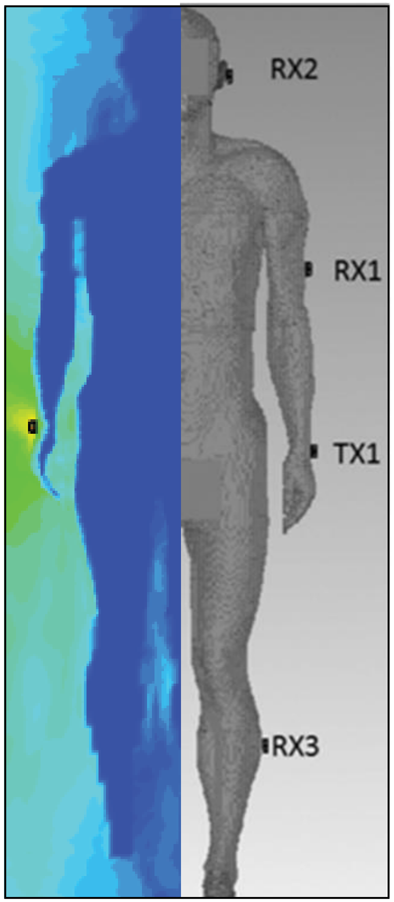


Smart clothing
Connected textiles for sports

Positioning & gesture recognition
Touchless interactions

5G and IoT
Millimeter-wave communications

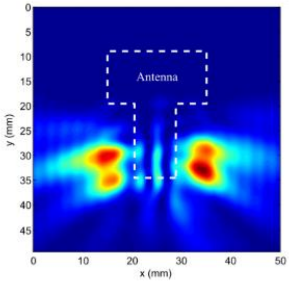
60-GHz band for body-centric applications



Antennas

Body models

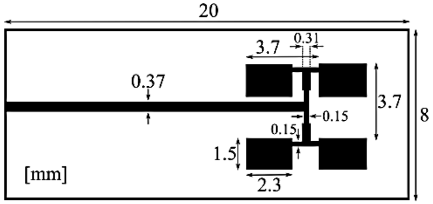
Dosimetry

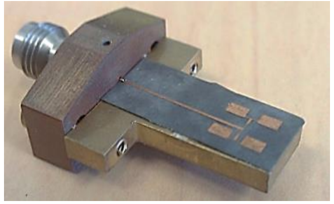


First mmW antennas for body-centric communications

On the classical substrate

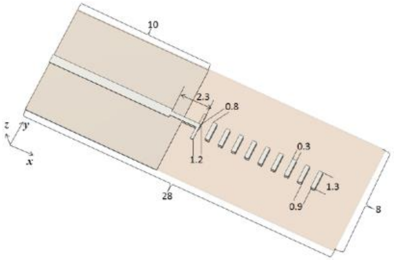
(127 or 254 µm RT Duroid 5880; ε_r =2.2; tanδ =0.003)

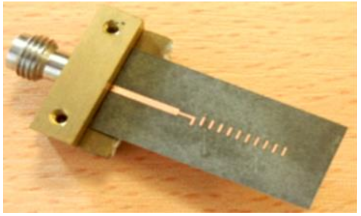




Antenna for off-body communications
(*broadside, 57-65 GHz, gain 12 dBi*)

N. Chahat, M. Zhadobov et al. IEEE AP, 60(12), 2012.



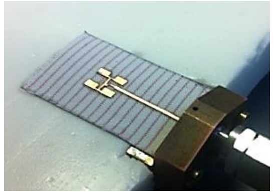


Antenna for on-body communications
(*end-fire, 55-65 GHz, gain 12 dBi*)

A. Guraliuc, N. Chahat, C. Leduc, M. Zhadobov et al. Electronics, 60(12), 2012.

Textile antennas

(200 µm cotton; ε_r =1.5; tanδ = 0.016)



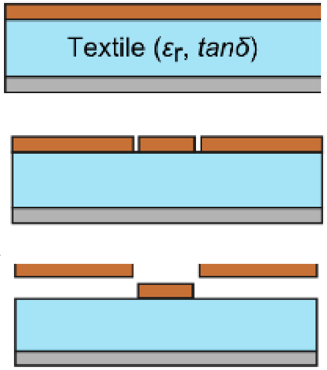
57-65 GHz, gain 8 dBi

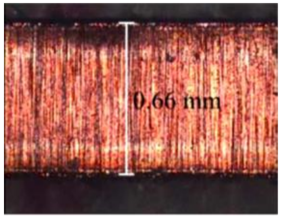
N. Chahat, M. Zhadobov et al. IEEE AP, 61(4), 2013.

55-67 GHz, gain 11.9 dBi

N. Chahat, M. Zhadobov et al. IEEE AWPL, 11, 2012.

Textile antenna fabrication using laser ablations (ProtoLaser S)





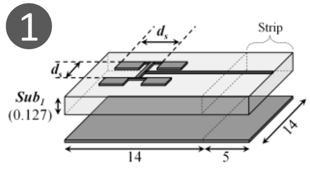
Fabrication precision < 10 µm

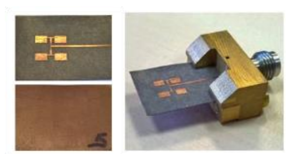
Impact of the feeding type on SAR and ΔT

Four-patch antenna arrays at 60 GHz

1

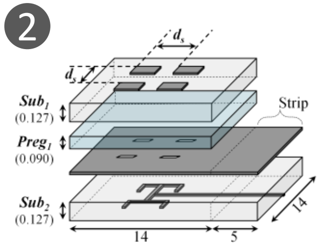
Excited by a micro-strip line, with a ground plane

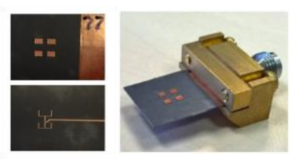




2

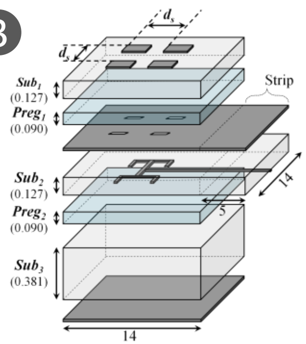
Aperture-coupled array excited by a microstrip line, without a ground plane

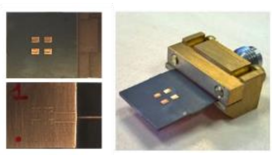




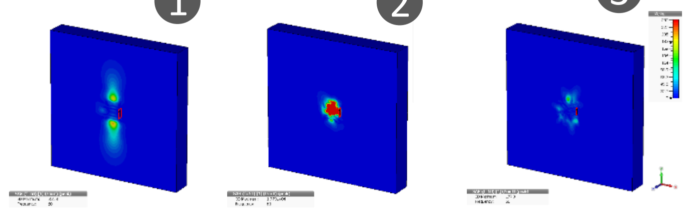
3

Aperture-coupled array, with a ground plane



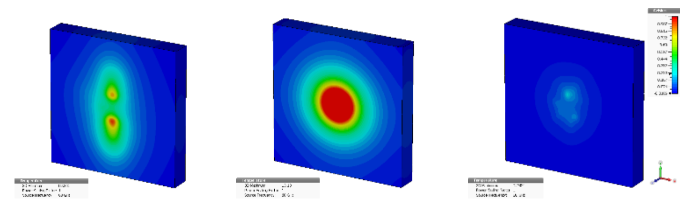


1 2 3



SAR

59% 100% 8% Absorbed power

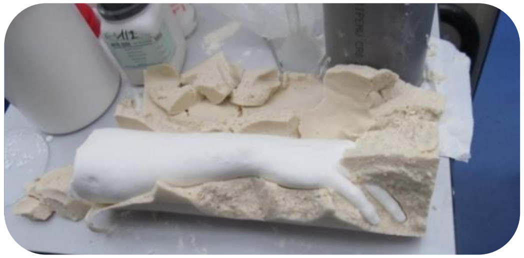


ΔT

- Local absorption ⇒ high SAR ⇒ ΔT
- Reduction of side lobes
- Presence of a ground plane

C. Leduc and M. Zhadobov. IEEE T-AP, 65(12), 2017.

First semi-solid skin-equivalent phantom covering 55-65 GHz range



Composition

1. **Deionized water (100g)**
2. Agar (1.5g)
3. Polyethylene powder (20g)
4. TX-151 (2g)
5. Sodium azide (0.1g)

	ε_r	σ (S/m)	R
Phantom	7.3	32.8	0.36
Skin	7.98	36.4	0.38

Applications

- On-body **antenna** measurements
- **Dosimetry**
- Body-centric **propagation** studies

Drawback of semi-solid phantoms

Short life time due to evaporation

N. Chahat, M. Zhadobov, R. Sauleau. Broadband tissue-equivalent phantom for BAN applications at mmW. *IEEE T-MTT.*, 60(7), pp. 2259-2266, 2012.

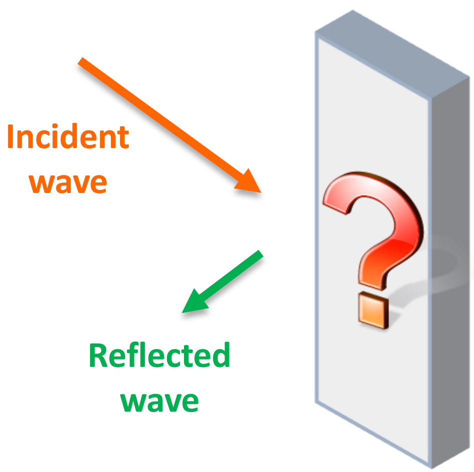
Solid skin-equivalent phantom at 60 GHz

Is it possible to create a skin-equivalent phantom **without water**?

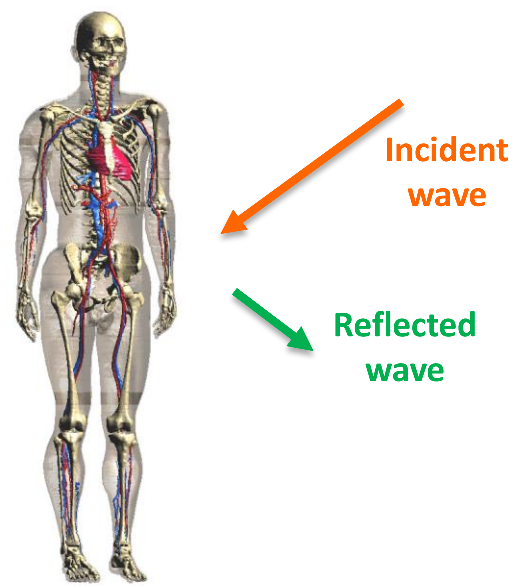
Complex permittivity of dry skin at 60 GHz is 7.98 – *j*10.9

Alternative solution

Solid phantom with the **same power reflection coefficient R** as that of skin



$$R_{phantom} = R_{skin}$$



Solid skin-equivalent phantom at 60 GHz

Composition

PDMS

Carbon powder

Metallic backing

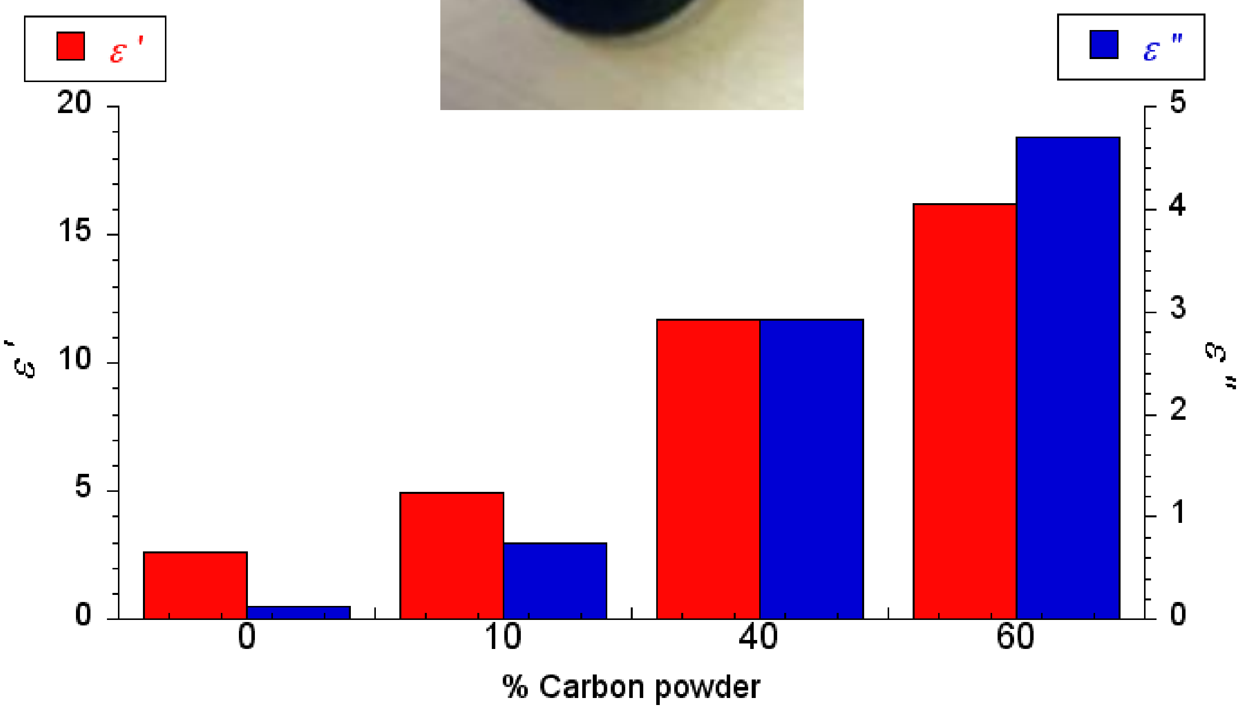
Fabrication

1. PDMS - 10 (silicone gel) : 1 (curing agent)
2. Degas PDMS
3. Mix PDMS with Carbon powder
4. Degas dielectric composite (carbon-PDMS)
5. Dry dielectric composite
6. Deposit metallic backing

SOLID SKIN-EQUIVALENT PHANTOM AT 60 GHZ

ε^*_{skin} @ 60 GHz = 7.98 – j10.9

Measured permittivity of PDMS / carbon mixture

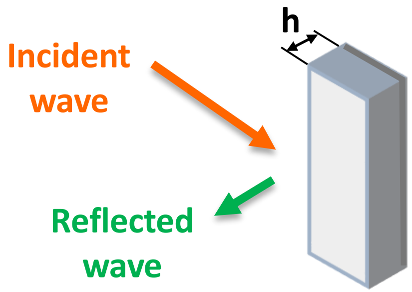


ε* increases with carbon concentration

ε'' is more than 2 times lower than ε'' of skin

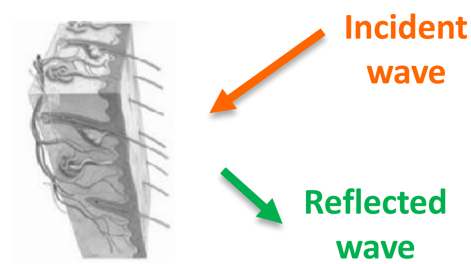
SOLID SKIN-EQUIVALENT PHANTOM AT 60 GHZ

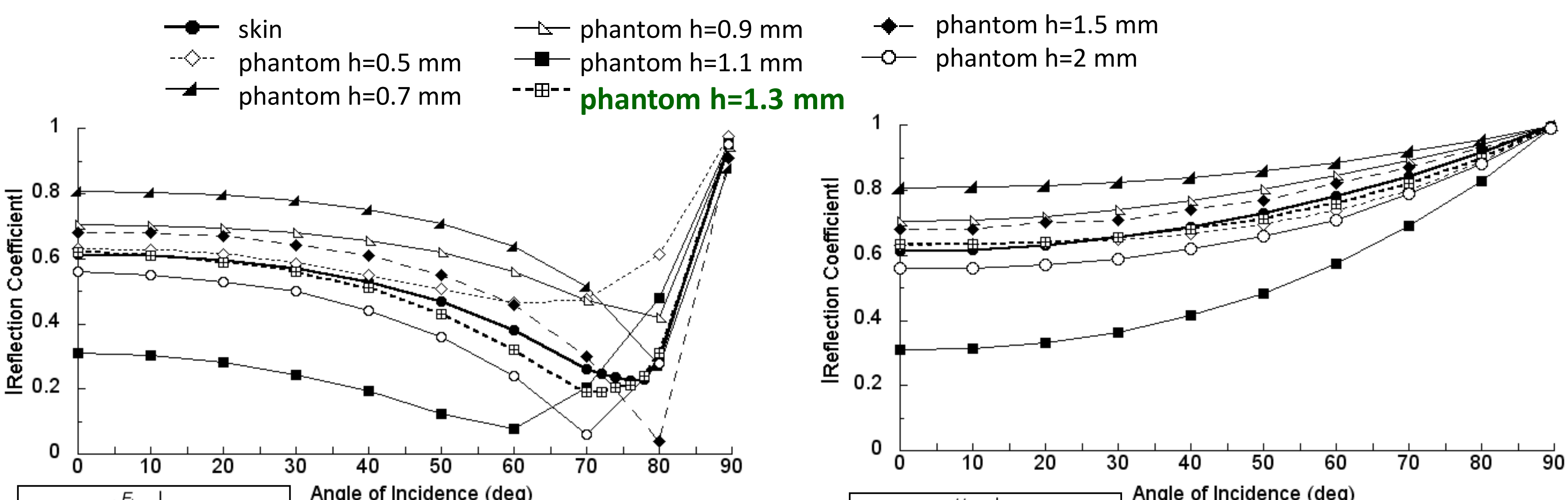
Computed R as a function of thickness

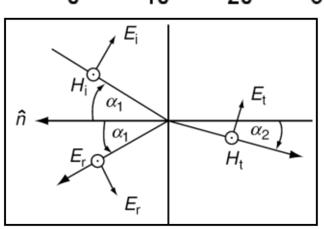


$R_{phantom}$ vs. R_{skin}

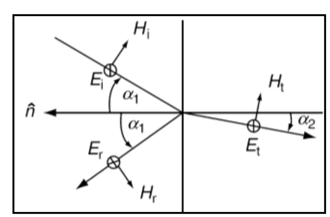
for **h = 0.5 – 2 mm**







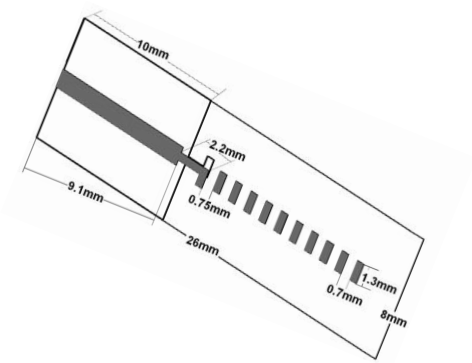
TM (parallel) polarization

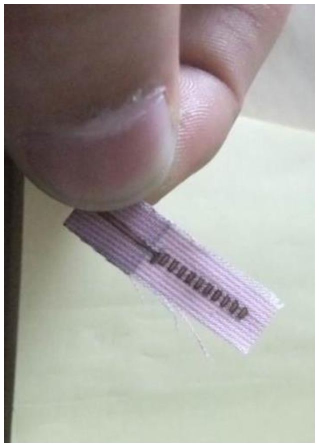


TE (perpendicular) polarization

Propagation between two wearable Yagi-Uda antennas at 60 GHz

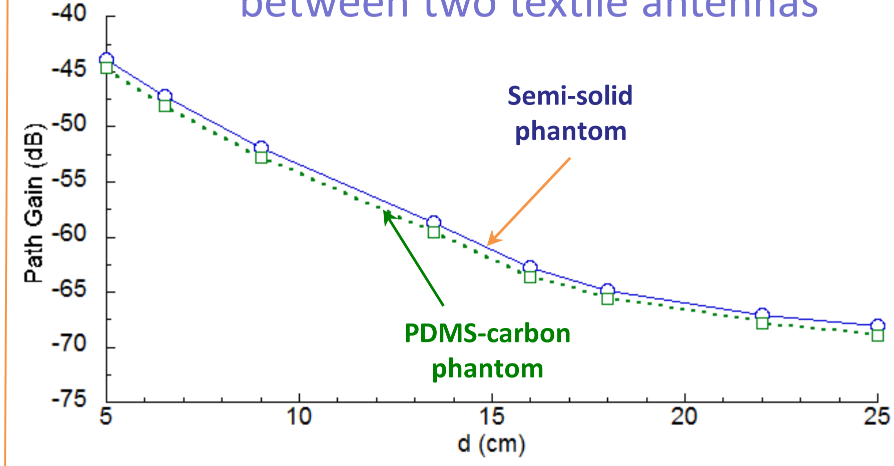
Yagi-Uda antenna design





N. Chahat, M. Zhadobov, et al. 60-GHz textile antenna array for body-centric communications. *IEEE T-AP,* 61(4), pp. 1816 - 1824, 2013.

Measured path gain at 60 GHz vs distance between two textile antennas



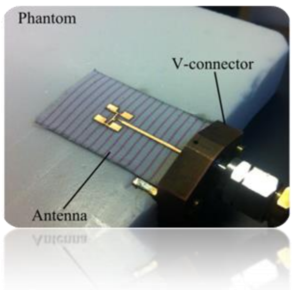
Difference less than 1 dB

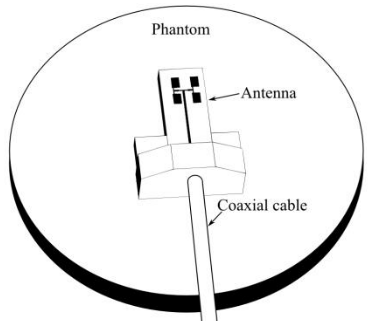
- **Accurate representation of the skin reflection coef.** (within 58-63 GHz range)
- **Extended lifetime** (years)
- **Reduced quantity of material needed for fabrication and low profile** ("surface" phantom)

Dosimetry method based on IR thermometry

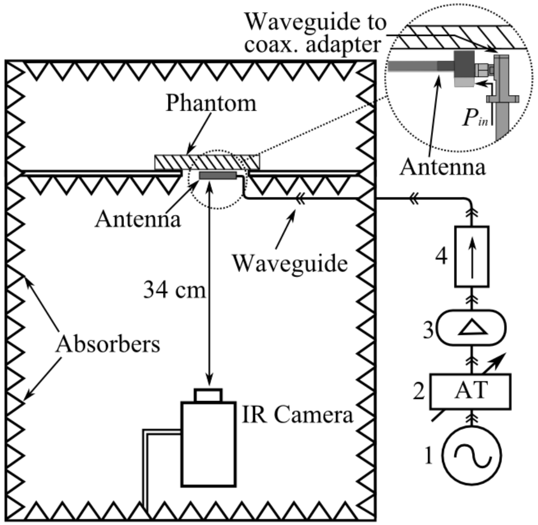
Determining $T(r,t) \Rightarrow SAR(r) \Rightarrow IPD_{eq}(r)$ in the near field

Antenna on a phantom





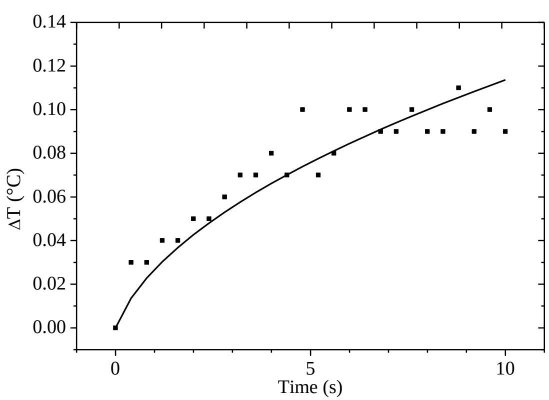
Absorption in the body

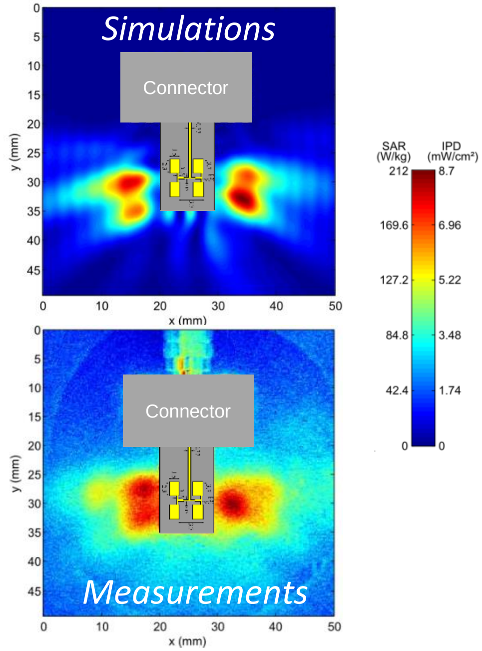


Compact anechoic chamber

(measurement using a high-resolution IR camera)

SAR and IPD distributions

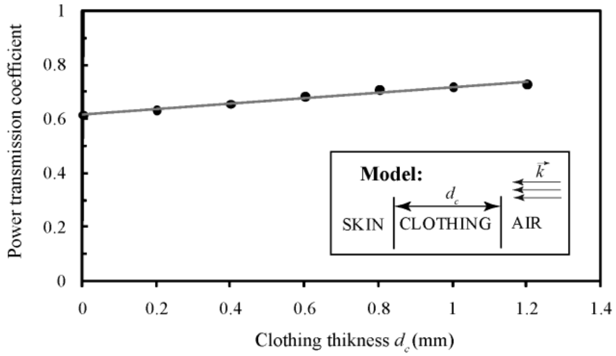


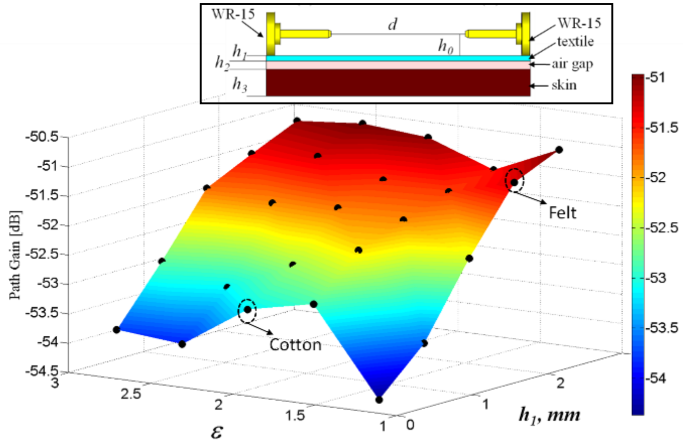


N. Chahat, M. Zhadobov et al. IEEE AP, 60(12), 2012.

IMPACT OF TEXTILES

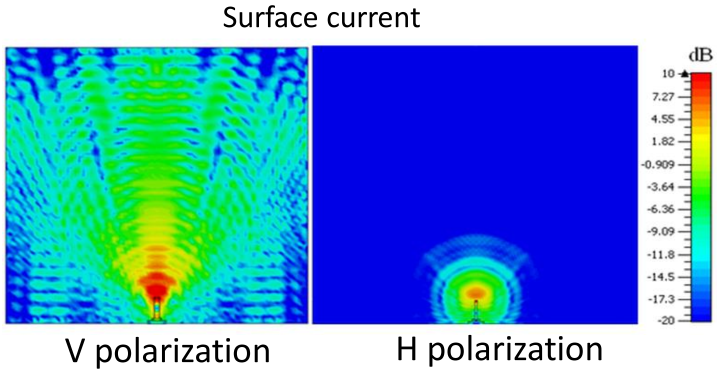
Regular textiles

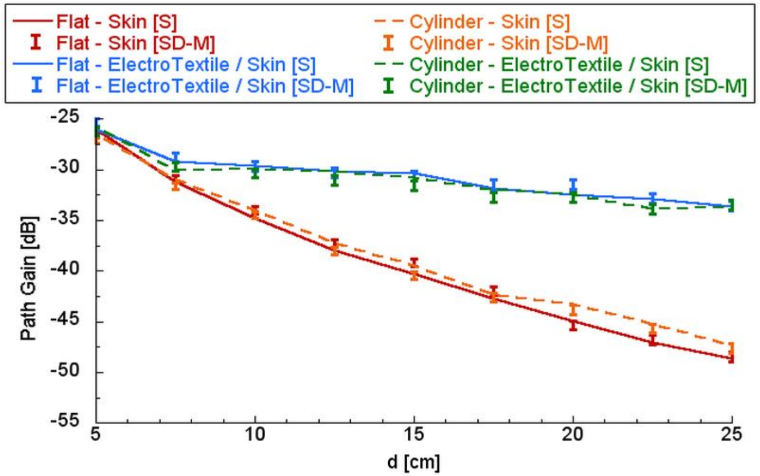




A. R. Guraliuc, M. Zhadobov et al. Effect of textile on the propagation along the body at 60 GHz. *IEEE T-AP,* 62(3), 2014.

Electro textile



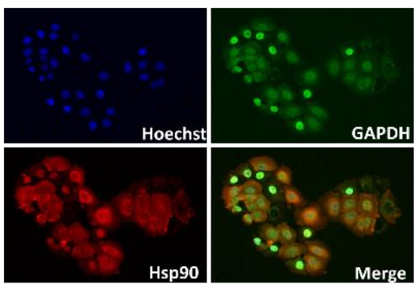


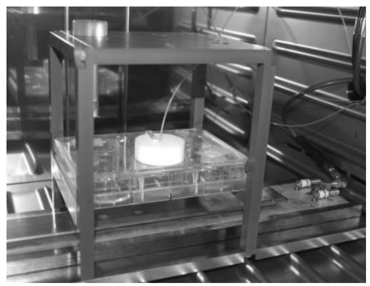
A. R. Guraliuc, M. Zhadobov et al. Enhancement of on-body propagation at 60 GHz using electro textiles. *IEEE AWPL*, 13, 2014.

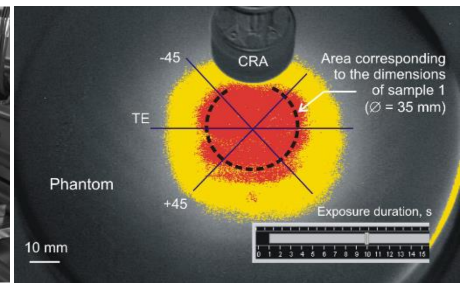
<u>Enhancement of propagation</u> along the body and <u>reduction of SAR</u> (by 97%) **using electro textiles**

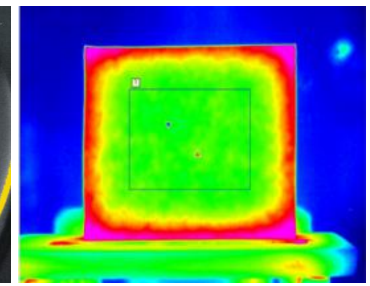
EXPOSURE SYSTEMS FOR *IN VITRO* AND *IN VIVO* STUDIES

Design and optimization of specific exposure systems equipped with dosimetric tools



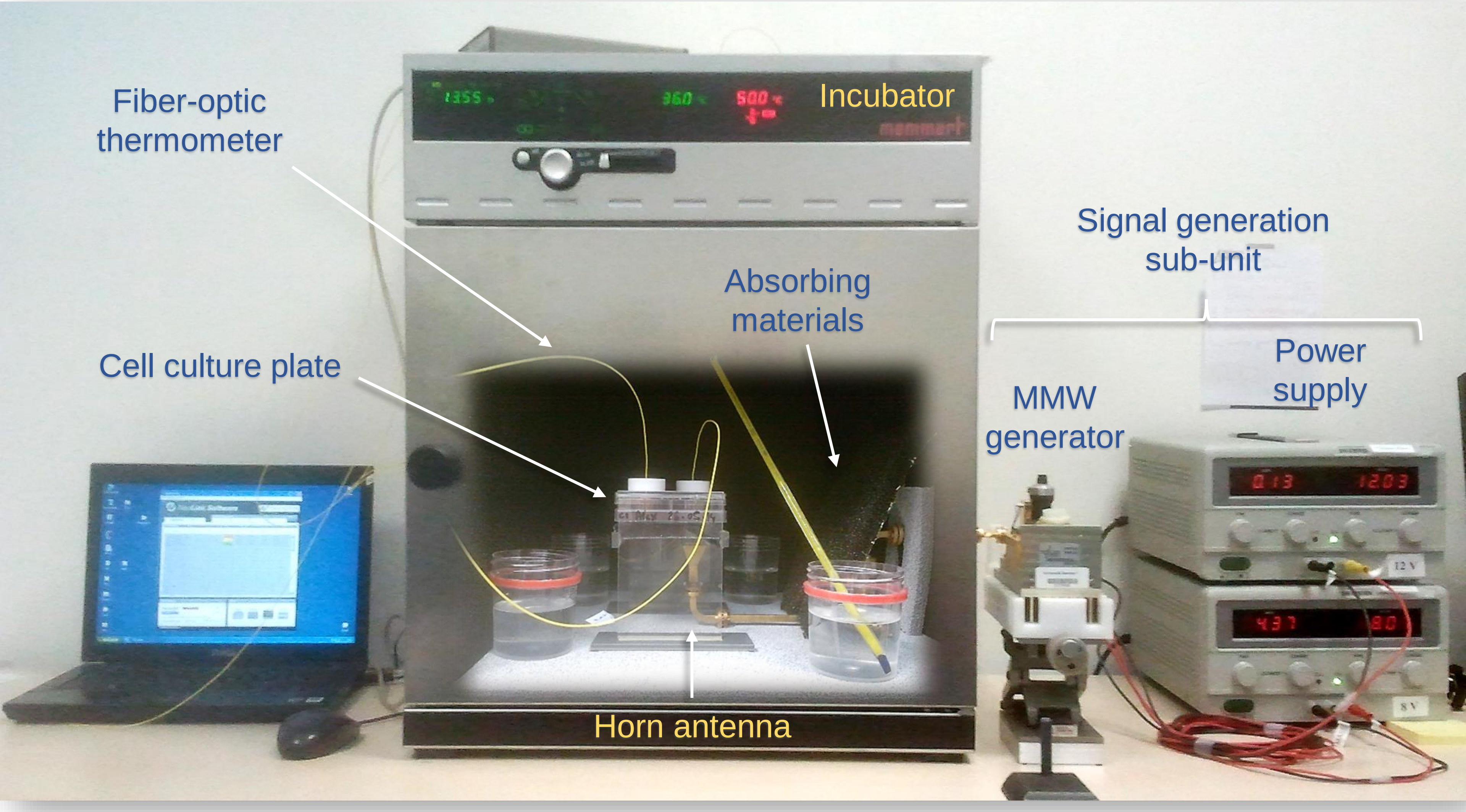






Challenges: control of the exposure parameters (*IPD, SAR, T in the near field*), optimization of the radiating structures and exposure systems, innovative dosimetric tools for reverberating environments

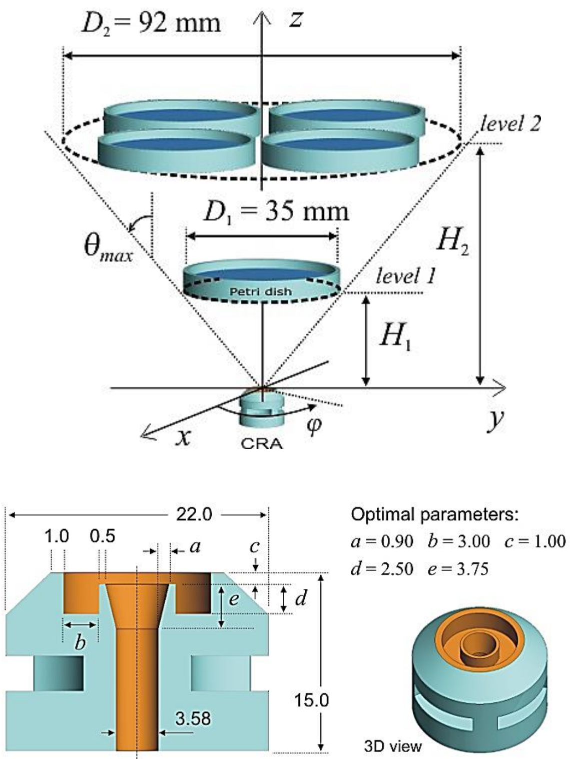
EXAMPLE OF EXPOSURE SYSTEM FOR *IN VITRO* STUDIES



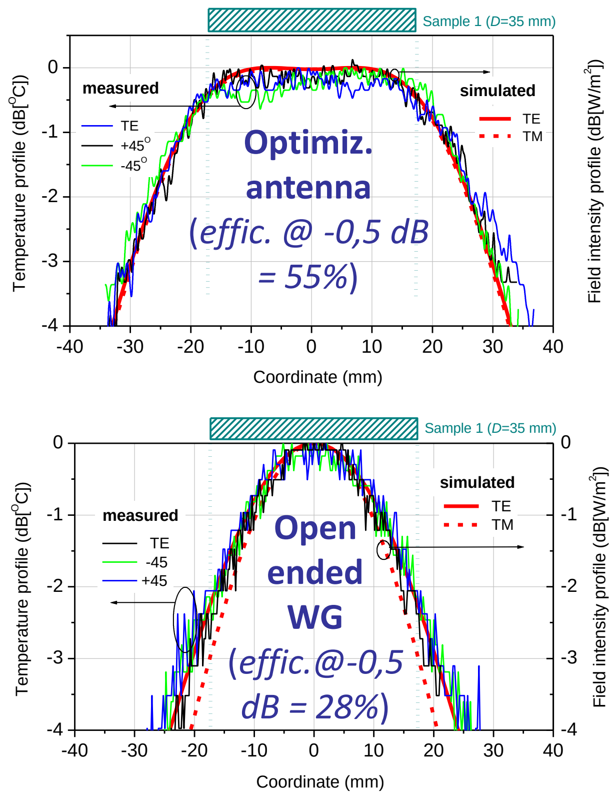
A. Haas, Y. Le Page, M. Zhadobov, R. Sauleau, Y. Le Drean. *Neuroscience Letters*, 618, pp. 58 – 65, 2016.
A. Haas, Y. Le Page, M. Zhadobov, A. Boriskin, R. Sauleau, Y. Le Drean. *Bioelectromagnetics*, 37(7), pp. 444 – 454, 2016.
A. Haas, Y. Le Page, M. Zhadobov, R. Sauleau, Y. Le Dréan, C. Saligaut. *Journal of Radiation Research*, pp. 1 – 7, 2017.

OPTIMIZATION OF RADIATING STRUCTURES FOR *IN VITRO* STUDIES

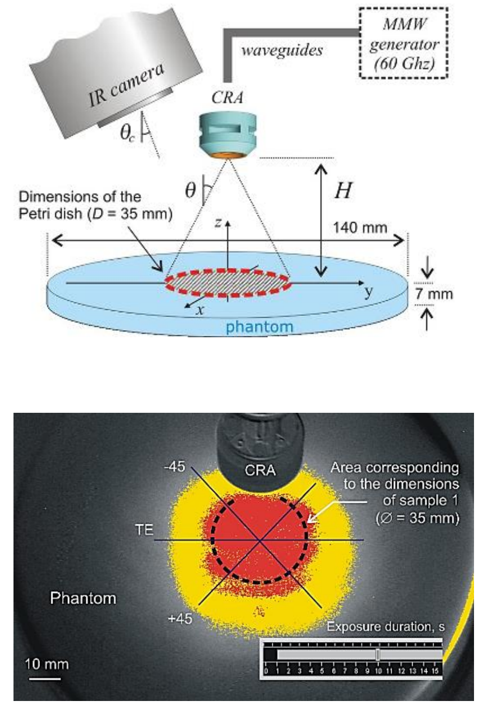
↗ uniformity and efficiency of exposure at 60 GHz



Considered exposure scenario and optimized choke ring antenna



Field intensity distribution



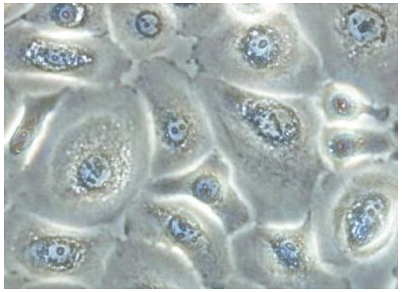
Experimental validation in the near field

A.V. Boriskin, M. Zhadobov et al. IEEE MTT, 61(5), 2013.

A.V. Boriskin, M. Zhadobov et al. IEEE AWPL, 13, 2014.

GENE EXPRESSION AS A SIGNATURE OF CELL STATUS IN A PARTICULAR ENVIRONMENTAL CONTEXT

In vitro cell culture



MMW

Can exposure interfere with cellular homeostasis ?

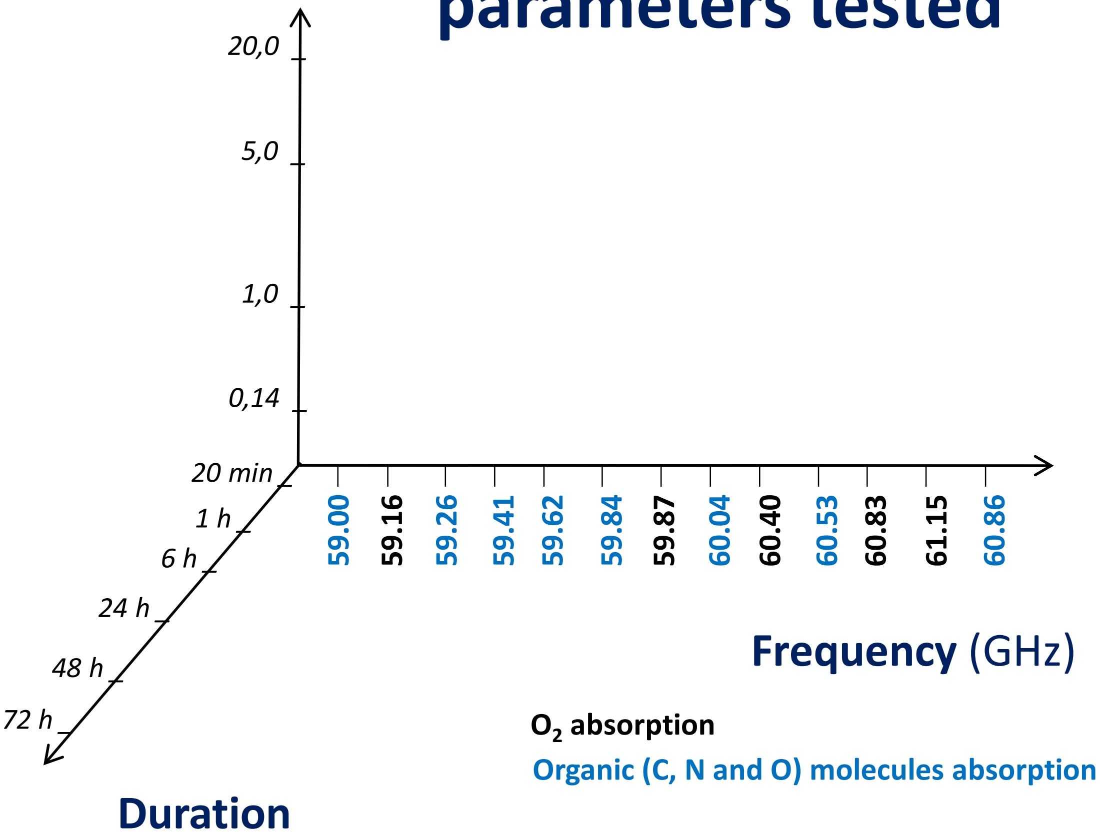
If yes:

Synthesis of factors allowing a rescue

MolecularBiology &Techniques

Genes involved in stress response specifically studied	**High-throughput studies**	
	Measurement of global DNA methylation and histone modifications	**DNA**
Transfection of reporter genes		transcription
RT-PCR	DNA microarray	**RNA**
		translation
Western-blot Immunocytofluorescence		**Protein**

Many exposure parameters tested



If athermic condition

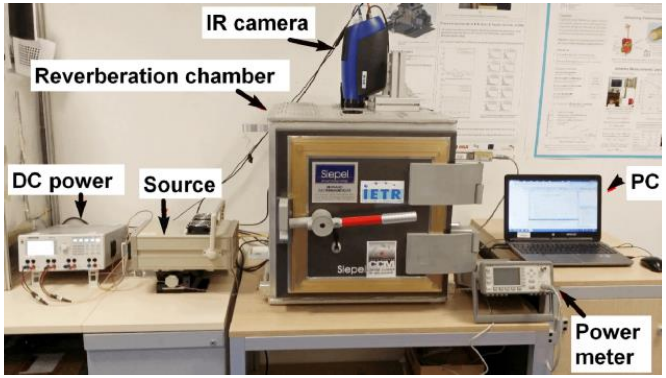
No, or very weak, modification of gene expression

Limits of the model

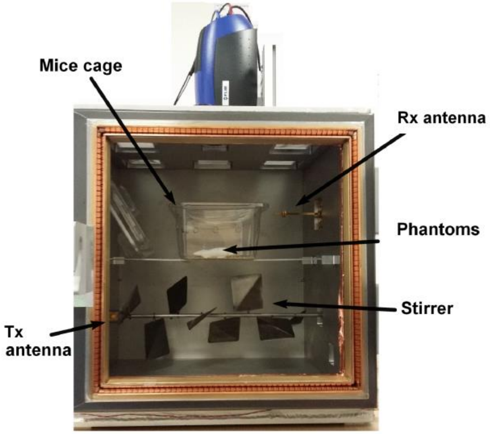
- Short-term exposure
- *In vitro* experiment

FIRST REVERBERATION CHAMBER AT MMW

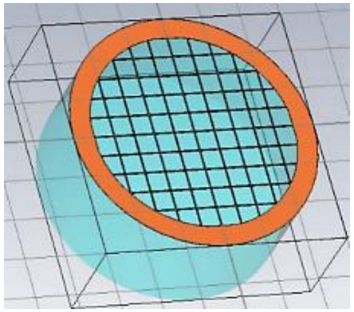
Application to *in vivo* studies (isotropic exposure)



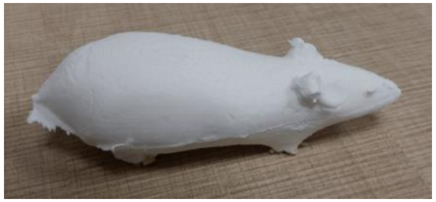
Reverberation chamber for *in vivo* exposure at mmW

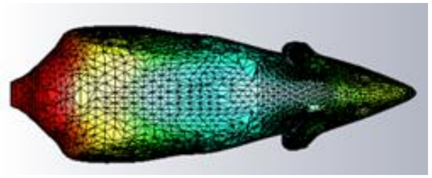


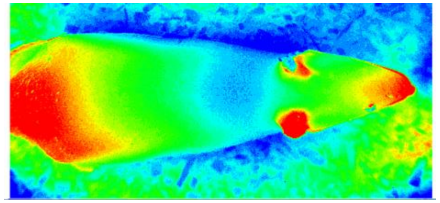
Internal view of the chamber



Interface for dosimetry (transparent at IR and opaque at mmW)







Example of results obtained using IR camera and skin-equivalent phantom

A. K. Fall, M. Zhadobov et al. Submitted to Bioelectromagnetics Journal (2019).

A. K. Fall, P. Besnier, C. Lemoine, M. Zhadobov et al. IEEE EMC, 75(1), 2015.

Thank you!