IV CONVEGNO NAZIONALE

Controllo ambientale degli agenti fisici: nuove prospettive e problematiche emergenti

Modelli per la valutazione delle grandezze dosimetriche e la verifica dei limiti relativi a campi elettromagnetici a RF

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Outline

Introduction

RF & MW Dosimetry

Numerical Dosimetry

Ad-Hoc Simulation Example

Conclusions

Rationale: EM Exposure

Human interaction with EM fields is frequent in a large range of frequencies! Ex: wireless devices (Wi-Fi, UMTS, Blue-Tooth, RBAs, etc) in RF and MW range, and high-power transmission line and home-appliances at lower frequencies.

Rationale: EM Exposure

EU Directive 2008/46/CE establishes that “Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with Directive 2004/40/CE no later than **30 April 2012**…… “

Directive 2004/40/CE of the European Parliament and of the Council establishes minimum health and safety requirements to protect workers against the risks arising from exposure to electromagnetic fields.

The exposure limit values must not be exceeded and they are to be considered as an integral part of a comprehensive system to limit the exposure of workers to electromagnetic fields. **Indeed the directive develops in some detail measures and provisions relating to the responsibility of employers**…….

For this directive which concerns workers exposed to electromagnetic fields and not patients nor the general public, **only known short-term adverse effects** in the human body are considered.

Dosimetry

In order to experimentally corroborate any interaction mechanism, the preliminary step is the evaluation of the electric and magnetic field intensities, and/or electromagnetic power density in situ

Dosimetry

Scientific discipline for the measurement or the determination by calculations of the internal electric field strength or induced current density, or of the specific absorption rate (SAR) distributions, in humans or animals exposed to electromagnetic fields and waves.

- Biological effects
- Setting of safety standards
- Compliance of devices

Dosimetric Parameters

Basic dosimetric parameters are the current density J [A/m] and the specific absorption rate (SAR) [W/kg].

SAR is the dosimetric measure that has been widely adopted at frequencies above about 100 kHz.

$$\mathrm{SAR} = \frac{\delta}{\delta t}\left(\frac{\delta W}{\delta m}\right)$$

$$SAR = \frac{\sigma\left|E^{2}\right|}{2\rho} = c\frac{\Delta T}{\Delta t}$$

In the context of RF and MW exposure these alternative forms are often used, allowing the SAR evaluation from either electric field or temperature measurement.

SAR

SAR is defined as the time derivation of the incremental energy absorbed by, or dissipated in, an incremental mass contained in a volume element of a given density.

SAR

Three different SAR are often used:

Whole Body SAR, 10g-SAR and 1g-SAR

- SAR values depend on the shape of the volume containing reference mass. Standardization is needed!

- The smaller is the mass, the better is the estimation! A large volume tend to artificially smooth out the SAR distribution!

$$SAR_{WB} = \frac{\int_{WB} \sigma |E|^2 / 2 \; dv}{\int_{WB} \rho \; dv}$$

$$SAR_{10g} = \frac{\int_{V-10g} \sigma |E|^2 / 2 \; dv}{\int_{V-10g} \rho \; dv}$$

$$SAR_{1g} = \frac{\int_{V-1g} \sigma |E|^2 / 2 \; dv}{\int_{V-1g} \rho \; dv}$$

Dosimetry typologies

Analytical Dosimetry

Experimental Dosimetry

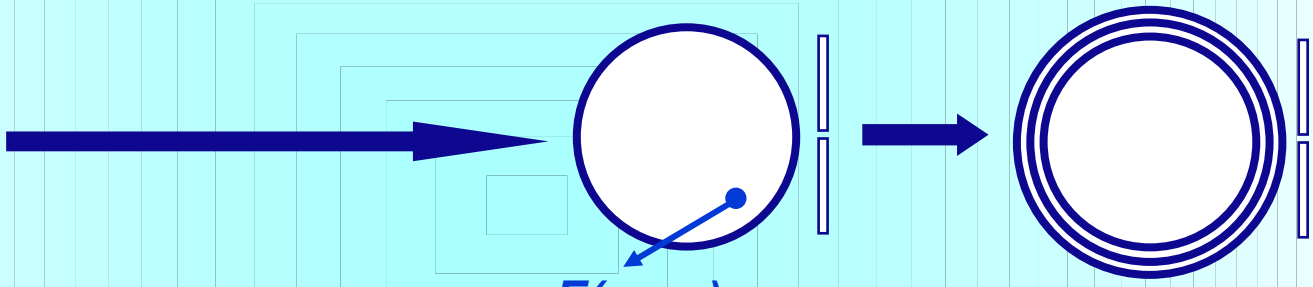
Numerical Dosimetry

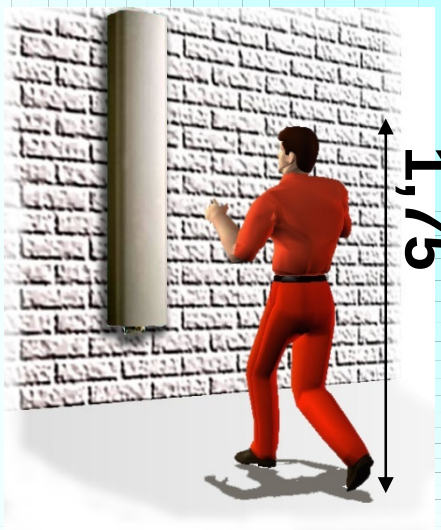
They have complementary characteristics

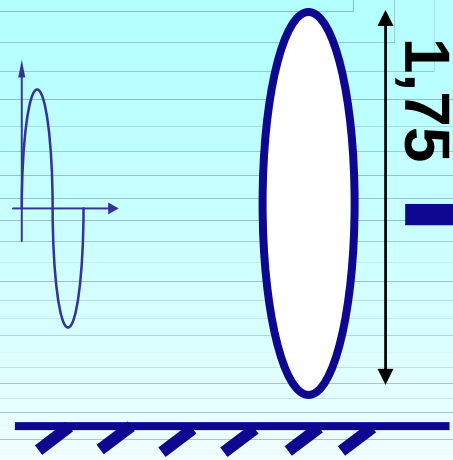
Joint use

Theoretical Dosimetry

An analytical model of the exposure problem is performed. Complicated cases cannot be modeled. Useful as “test case generator” for experimental and numerical dosimetry validation, and for a phenomenological first investigation of the problem.







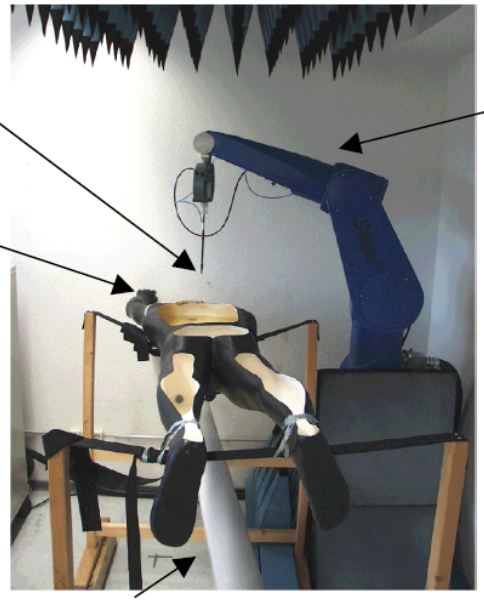
Absorption-dependence on frequency, polarization & environment (ground) can be deducted by analytical model

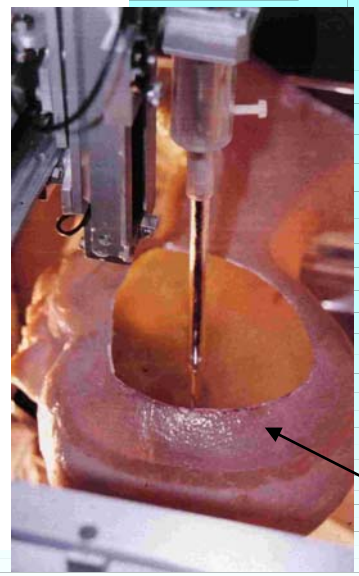
Experimental Dosimetry

- Need of adequate experimental set-up and often high operating costs

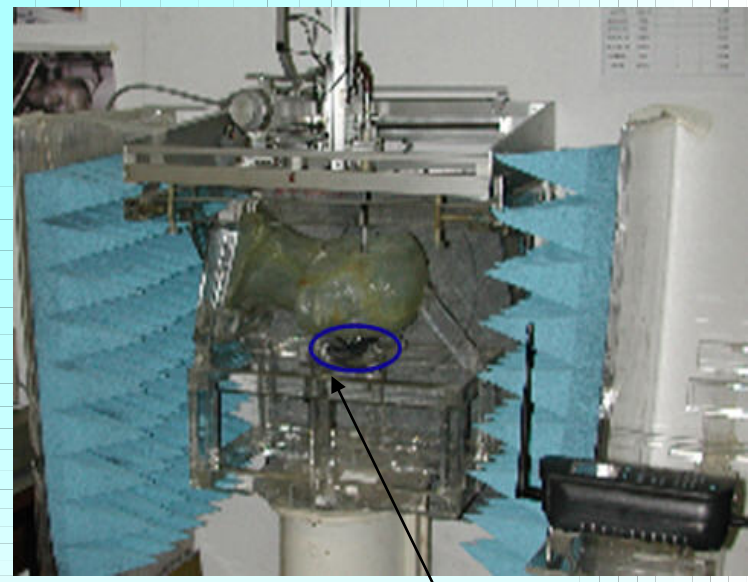
- Real sources can be used!

- Use of simplified human body models (filled with a synthetic liquid material) or animals; difficult correlation with SAR in real humans.





Simplified phantom

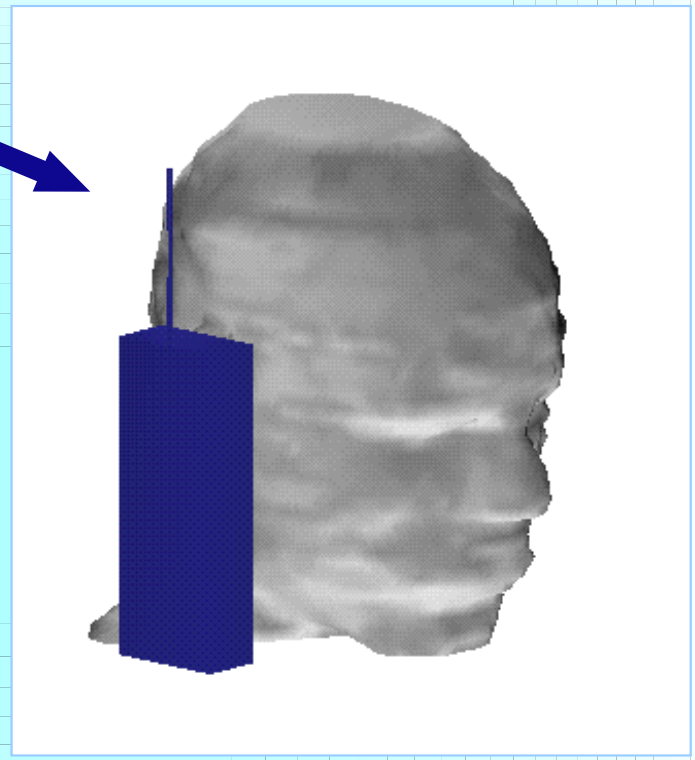


Mobile phone

Numerical Dosimetry

The human-antenna interaction problem is solved in full-wave form by numerically modeling source and human!

Complementary properties: High Resolution Heterogeneous numerical body models are available, but the numerical modeling of radiating sources is difficult because of its size and complexity.



Numerical Dosimetry needs:

- **A high quality numerical body model**
- **A robust and versatile EM solver**
- **Appropriate testing protocols**

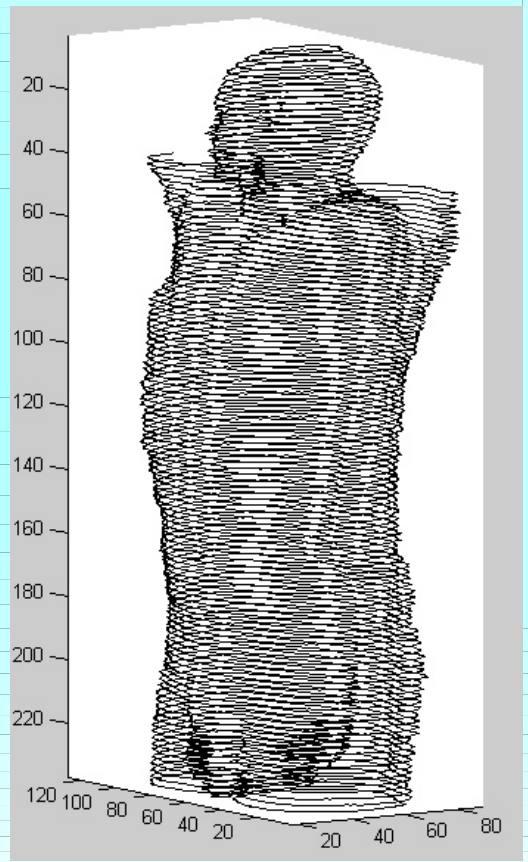
Numerical Phantoms

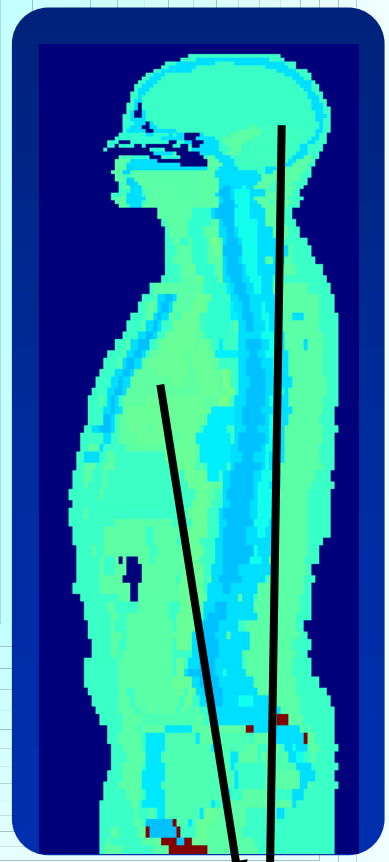
Many different human body models are available, with different shape and resolution.

They have been obtained by using a combination of Magnetic Resonance Images, photographic scans and Computer Tomography Images!

Each point of the numerical phantom is associated to the correspondent tissue..

Yale-Phantom: resolution 4mm, 128x128x243 voxels,





Different tissues

Numerical Phantoms

Each tissue must be associated to its permittivity and conductivity values… which are frequency dependent!

Tissue Dependence on Frequency:

Low Frequency: ε_r **large,** σ **small**

High Frequency: ε_r **small,** σ **large**

	835 MHz		1900 MHz	
Tissue	ε_r	σ (S/m)	ε_r	σ (S/m)
bone	17.4	0.25	16.40	0.45
muscle	51.76	1.11	49.41	1.64
fat	9.99	0.17	9.38	0.26
cartilage	40.69	0.82	38.10	1.28
brain & glands	45.26	0.92	43.22	1.29
skin	35.40	0.63	37.21	1.25

	835 MHz		1900 MHz	
Tissue	ε_r	σ (S/m)	ε_r	σ (S/m)
nerve	33.40	0.60	32.05	0.90
blood	55.50	1.86	54.20	2.27
CSF	78.10	1.97	77.30	2.55
eye humour	67.90	1.68	67.15	2.14
sclera	54.90	1.17	52.56	1.73
lens	36.59	0.51	42.02	1.15

* Provided by Camelia Gabriel

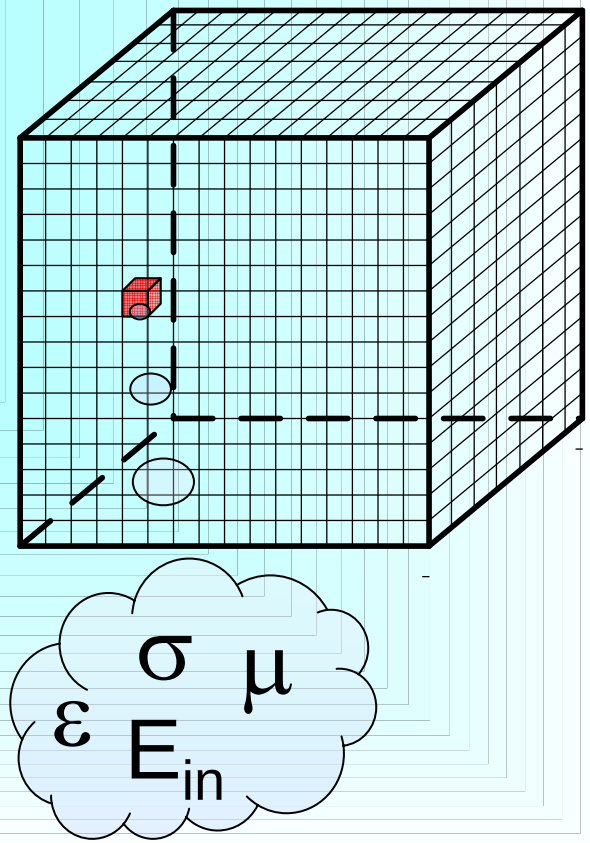
EM Solvers: FDTD

Among the available EM solvers, MoM, FEM & FDTD methods are the most adopted for dosimetric purposes. When heterogeneous models of human bodies with complicated shapes and inner dielectric characterization are modeled, FDTD emerges as the method of choice in many studies, thanks to its simplicity, flexibility and compatibility with the problem geometry.

FDTD algorithm [Yee 1966] is based on time and space discretization of Maxwells's curl equations.

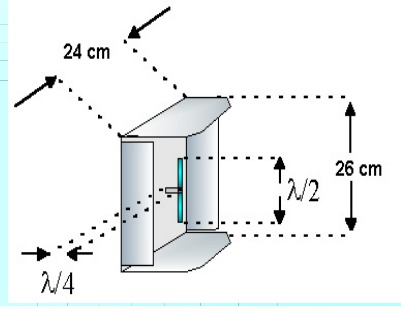
The space and time derivatives are approximated by using central finite discretization, resulting in second-order accurate expressions.

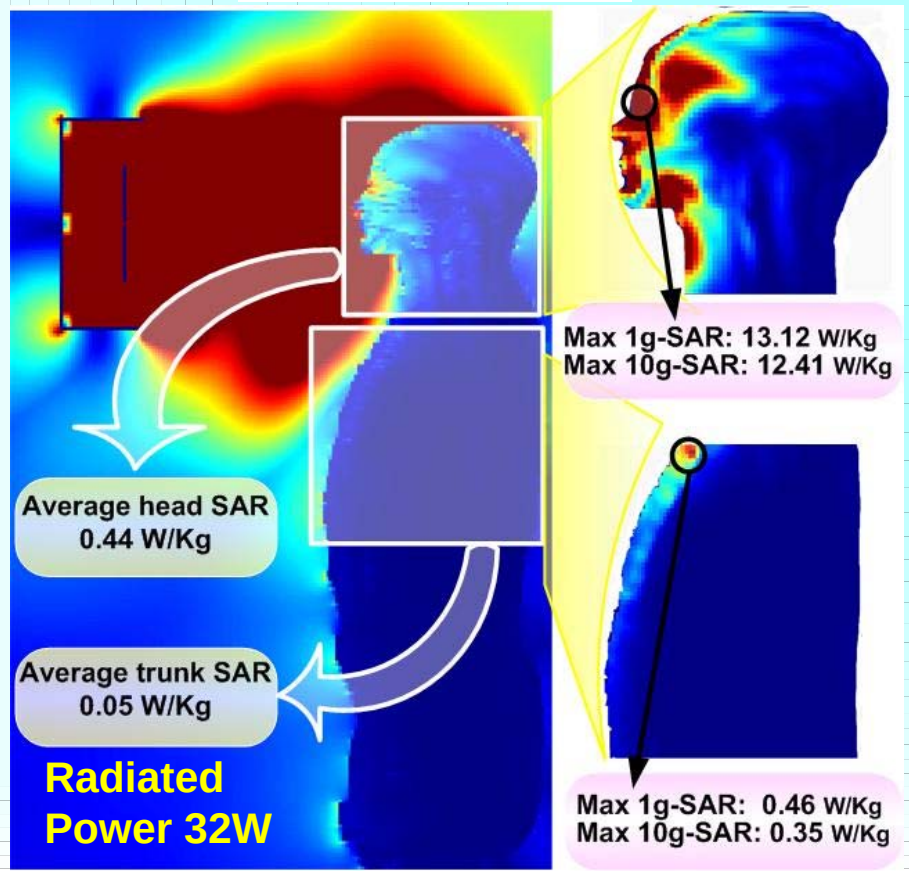
FDTD uses a leap frog method to solve Maxwell's equations. At each time step, EM fields are updated.



Real Simulation by using FDTD….

FDTD & SAR Evaluation





ICNIRP standard for workers

whole body average SAR :
<u>0.4 W/Kg</u>;

10g SAR in head or trunk point:
<u>10 W/Kg</u>;

10g SAR in limb point:
<u>20 W/Kg</u>.

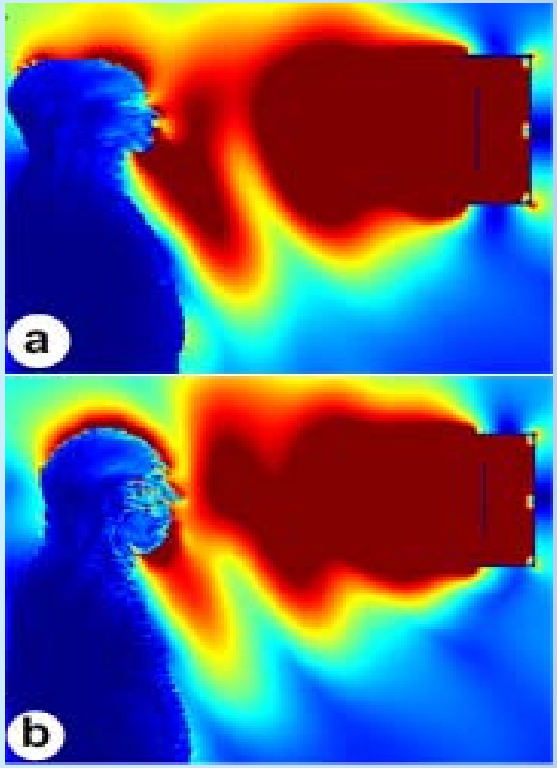
Dosimetry Application 1: SAR evaluation in different numerical phantoms

Many different numerical phantoms have been exposed to the field emitted by a 900 MHz source, in order to answer the different questions: how much is it the impact of the numerical model on the dosimetric study? How much is it the impact of the use of homogeneous numerical models?

A very complex parallel FDTD algorithm has been used and EM field and SAR have been evaluated in each phantom points.

It will be shown how difficult is the result interpretation even by using accurate tools.

Numerical Phantoms



Yale Phantom: voxel size 4mm^3.

No limbs are modeled

Brooks Phantom: voxel size 3mm^3.

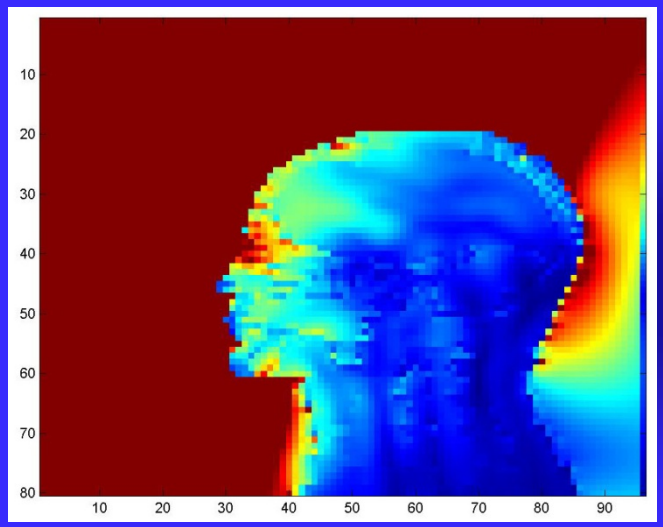
Whole body phantom

The 2 phantoms have been simplified by assuming a homogeneous inner structure. Some new phantoms have been generated considering the YP and BP averaged values.

	BP	BHP	BH_YP	BH_BP	YP	YHP	YH_YP	YH_BP
Heter./Homog.	Het.	Hom.	Hom.	Hom.	Het.	Hom.	Hom.	Hom.
permittivity ε	/	50	46.33	34.32	/	50	46.33	34.32
conductivity σ [S/m]	/	0.92	0.73	0.63	/	0.92	0.73	0.63

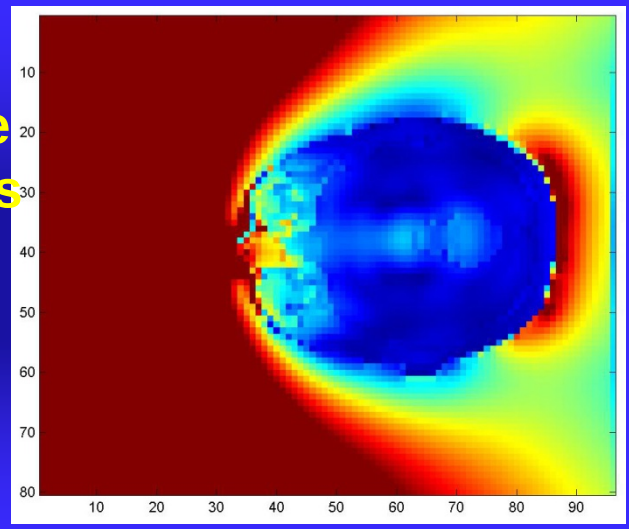
YH_BP = Yale-shape Homogeneous-Brooks Phantom

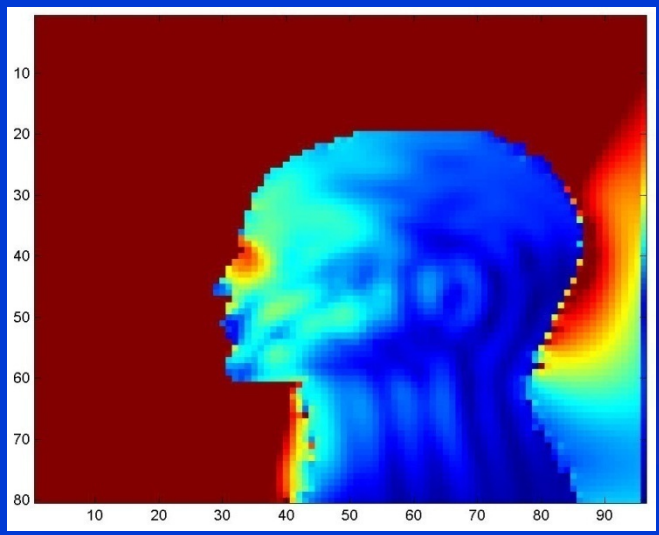
Heterogeneous Vs Homogeneous



E-Field in Yale Heterogeneous Phantom

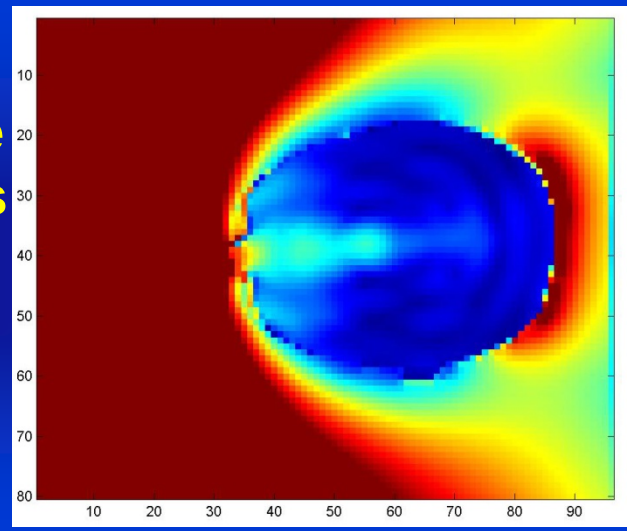
(YP)



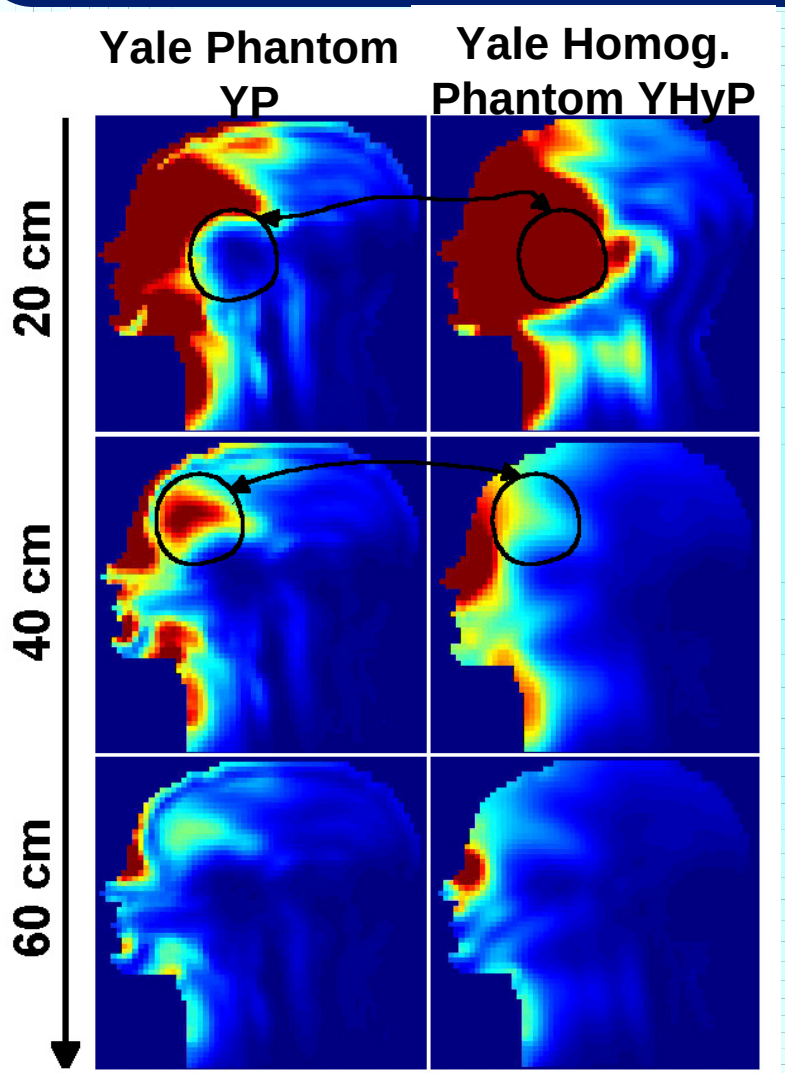


E-Field in Yale Homogeneous Phantom

(YH1P)



Heterogeneous Vs Homogeneous



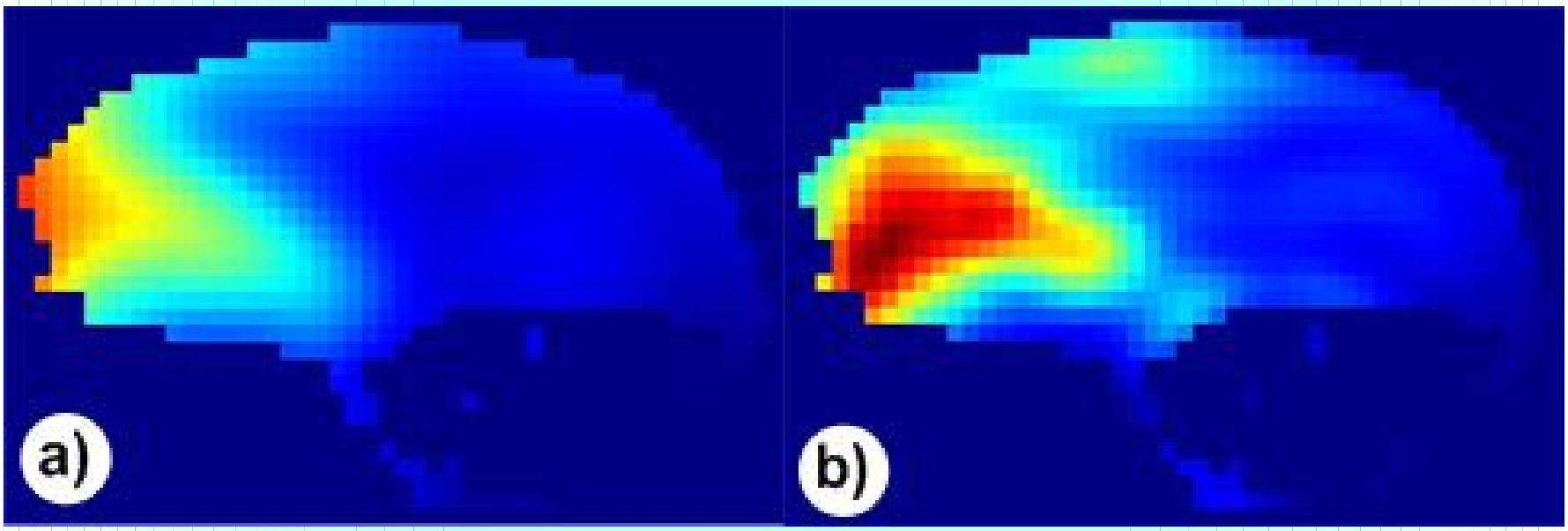
1g-SAR Levels

1g-peak-SAR and 10g-peak-SAR (Input power 32W)

	Heterogeneous phantom		Homogeneous Phantom	
distance	1g-SAR	10g-SAR	1g-SAR	10g-SAR
20 cm	30.32 [W/Kg]	15.30 [W/Kg]	29.52 [W/Kg]	16.62 [W/Kg]
30 cm	12.61 [W/Kg]	6.32 [W/Kg]	11.72 [W/Kg]	6.64 [W/Kg]
40 cm	10.68 [W/Kg]	5.31 [W/Kg]	9.98 [W/Kg]	5.62 [W/Kg]
50 cm	5.30 [W/Kg]	2.63 [W/Kg]	4.87 [W/Kg]	2.75 [W/Kg]
60 cm	4.67 [W/Kg]	2.30 [W/Kg]	4.34 [W/Kg]	2.47 [W/Kg]

Heterogeneous Vs Homogeneous

1g-SAR Levels

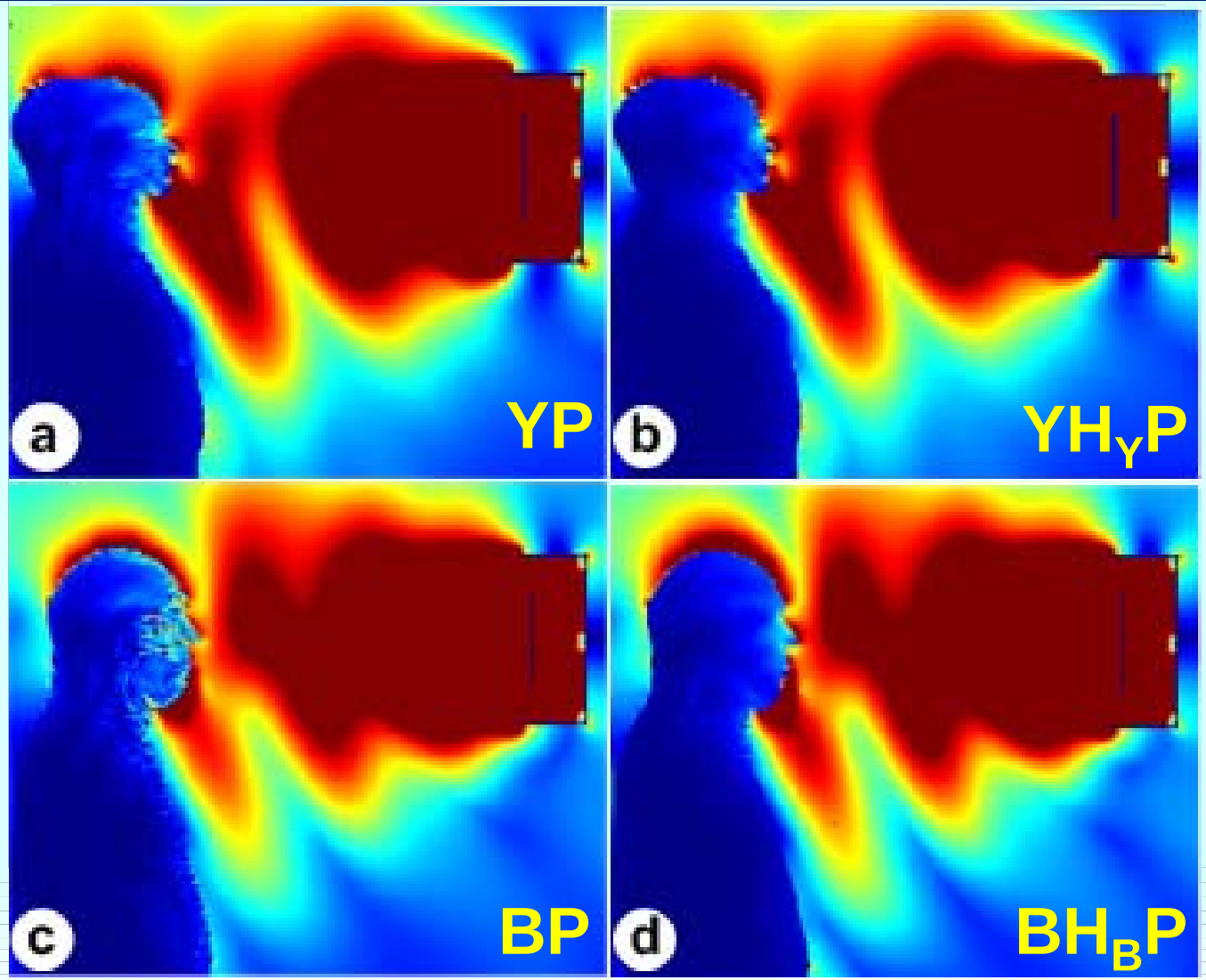


1g SAR level: YHyP a) and YP b) in the brain region.

Differences are evident!

Phantoms Modeled with Different Shape and Dielectric Characterization

Heterogeneous Yale a) and Brooks c)



Homogeneous Yale b) and Brooks d)

Phantom's Results Comparison

K730678 exposure: 1-g SAR and 10-g SAR peak values [W/Kg]							
Dist	type	YP	YH_YP	YH_BP	BP	BH_YP	BH_BP
20	1g	30.3246	29.5250	27.8730	18.4290	27.6260	25.7077
cm	10g	15.3094	16.6297	15.2104	11.8857	18.8416	17.2059
30	1g	12.6115	11.7294	11.4564	13.3806	19.5851	17.8272
cm	10g	6.3243	6.6411	6.2494	8.6443	13.4448	12.0284
40	1g	10.6837	9.9847	9.6198	6.1333	9.6302	9.1622
cm	10g	5.3198	5.6239	5.2419	4.1630	7.1555	6.5020
50	1g	5.3187	4.8766	4.7711	4.7905	7.0089	6.7971
cm	10g	2.6331	2.7527	2.5955	3.1065	5.2943	4.7935

	BP	BHP	BH_YP	BH_BP	YP	YHP	YH_YP	YH_BP
Heter./Homog.	Het.	Hom.	Hom.	Hom.	Het.	Hom.	Hom.	Hom.
permittivity ε	/	50	46.33	34.32	/	50	46.33	34.32
conductivity σ [S/m]	/	0.92	0.73	0.63	/	0.92	0.73	0.63

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permittivity ε	/	50	46.33	34.32	/	50	46.33	34.32
conductivity σ [S/m]	/	0.92	0.73	0.63	/	0.92	0.73	0.63

When comparing the two heterogeneous phantoms, differences of up to 40% are observed!!!

When comparing the heterogeneous phantom with its companion homogeneous versions, the difference between YP and its homogeneous version is smaller than the difference between BP and BH_BP.

Phantom's Results Comparison

K730678 exposure: 1-g SAR and 10-g SAR peak values [W/Kg]							
Dist	**type**	**YP**	**YH_YP**	**YH_BP**	**BP**	**BH_YP**	**BH_BP**
20 cm	**1g**	30.3246	29.5250	27.8730	18.4290	27.6260	25.7077
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	10g	2.6331	2.7527	2.5955	3.1065	5.2943	4.7935

	BP	BHP	BH_YP	BH_BP	YP	YHP	YH_YP	YH_BP
Heter./Homog.	Het.	Hom.	Hom.	Hom.	Het.	Hom.	Hom.	Hom.
permittivity ε	/	50	46.33	34.32	/	50	46.33	34.32
conductivity σ [S/m]	/	0.92	0.73	0.63	/	0.92	0.73	0.63

Effects of the phantom shape: by comparing homogeneous phantoms with different shape but similar dielectric characterization, the maximum difference is up to 50%!!

Phantom's Results Comparison

K730678 exposure: 1-g SAR and 10-g SAR peak values [W/Kg]							
Dist	**type**	**YP**	**YH_YP**	**YH_BP**	**BP**	**BH_YP**	**BH_BP**
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Heter./Homog.	Het.	Hom.	Hom.	Hom.	Het.	Hom.	Hom.	Hom.
permittivity ε	/	50	46.33	34.32	/	50	46.33	34.32
conductivity σ [S/m]	/	0.92	0.73	0.63	/	0.92	0.73	0.63

Effects of the phantom inner characterization: by comparing homogeneous phantoms with the same shape but different characterization (YH_YP with YH_BP and BH_YP with BH_BP), the difference in the permittivity and conductivity values (up to 30% for permittivity, up to 13% for the conductivity) causes small differences on the peak SAR estimation (in the range 2%-10%).

The differences on the SAR estimation by varying the phantom shape and/or characterization are quite impressive!

Peak SAR values are strongly influenced by the phantom shape above all because of the proximity of the peak to the external human surface.

Dosimetry Application 2: SAR algorithm differences

Different algorithms for the numerical evaluation of the SAR can be implemented and used.

The algorithms implemented in commercial tools are not well known.

Also in this case, it will be show how difficult is the result interpretation.

Specific Absorption Rate

Continuous Space

$$SAR_{rm} = \frac{\int_{V(rm)} \sigma |E|^2 / 2 \; dv}{\int_{V(rm)} \rho \; dv}$$

Discretized Space

$$SAR_{rm} = \frac{\sum_{i \in \bar{V}(rm)} (\sigma_i |E_i|^2 / 2) \Delta V_i}{\sum_{i \in \bar{V}(rm)} \rho_i \Delta V_i}$$

r m* =reference mass; *V(r m)*=Volume containing *r m

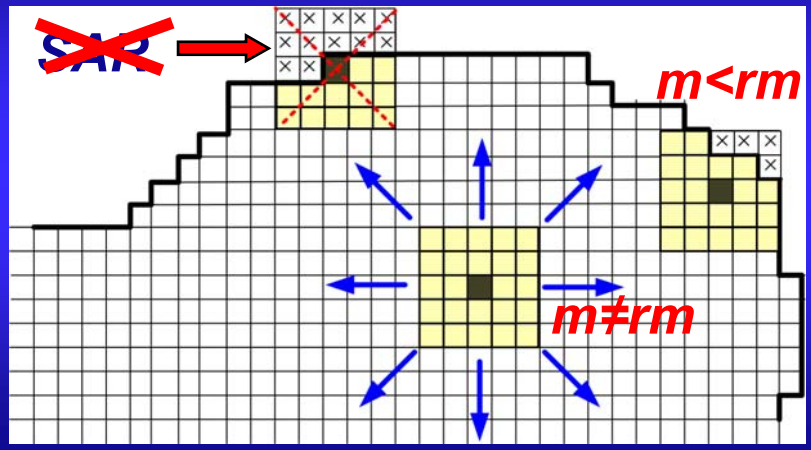
Does the shape of the volume containing the reference mass impact the SAR value?

Is the discretization step influent?

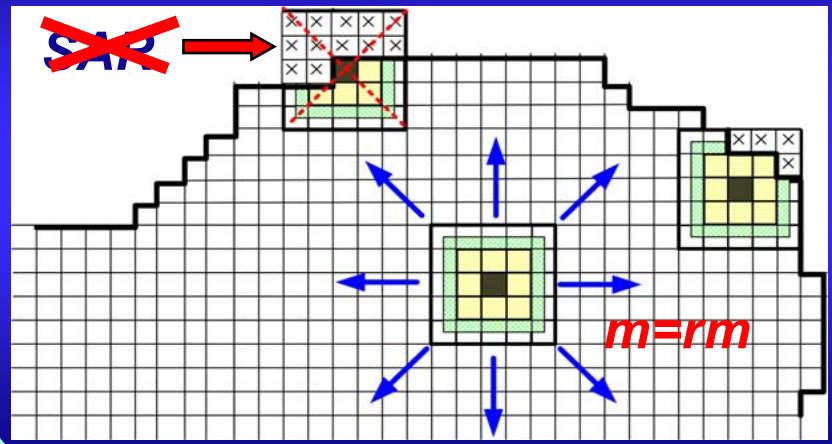
For points close to the surface the volume shape is modified. Which is the best algorithm in that sense?

Commonly Adopted Algorithms

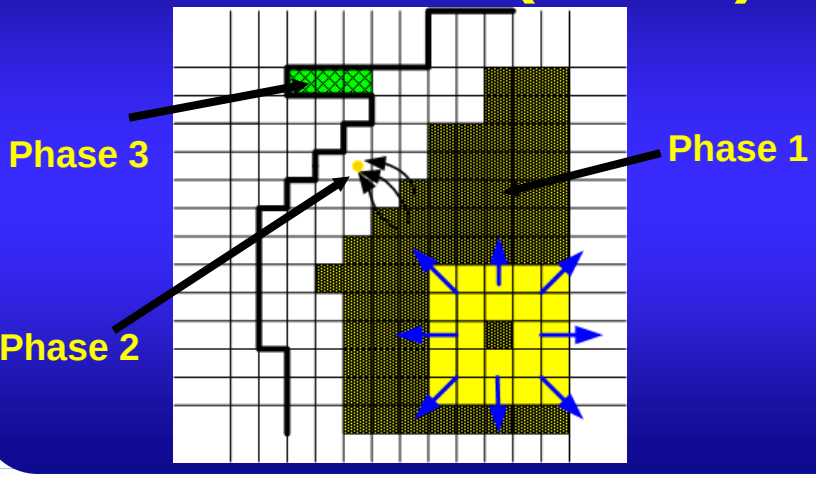
Fixed-Cube (FC)



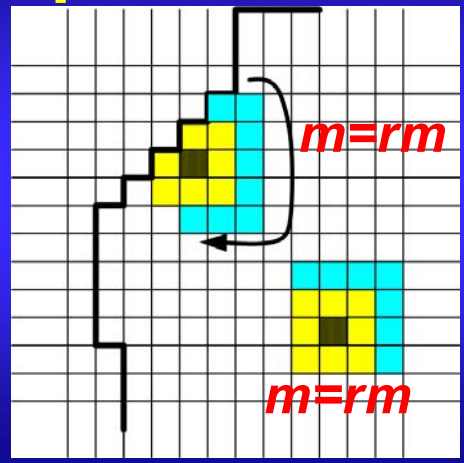
Fixed-Adj.-Cube (FAC)



IEEE C95.3 (C95.3)



Adaptive-Cube (AC)



Common Algorithms Vs Requirements

	Aver. Mass Toler. < 5%	*Independence on Ref. Syst.*	*Computability everywhere*	*Overall Accuracy*
FC	NO ☹	NO ☹	NO ☹☹	☹☹☹☹
FAC	YES ☺	NO ☹	NO ☹☹	☹☹
AC	YES ☺	NO 😐	YES ☺	😐
C95.3	NO ☹	NO ☹	YES 😐	☹☹☹☹

-None of the adopted algorithms satisfies the minimum requirements

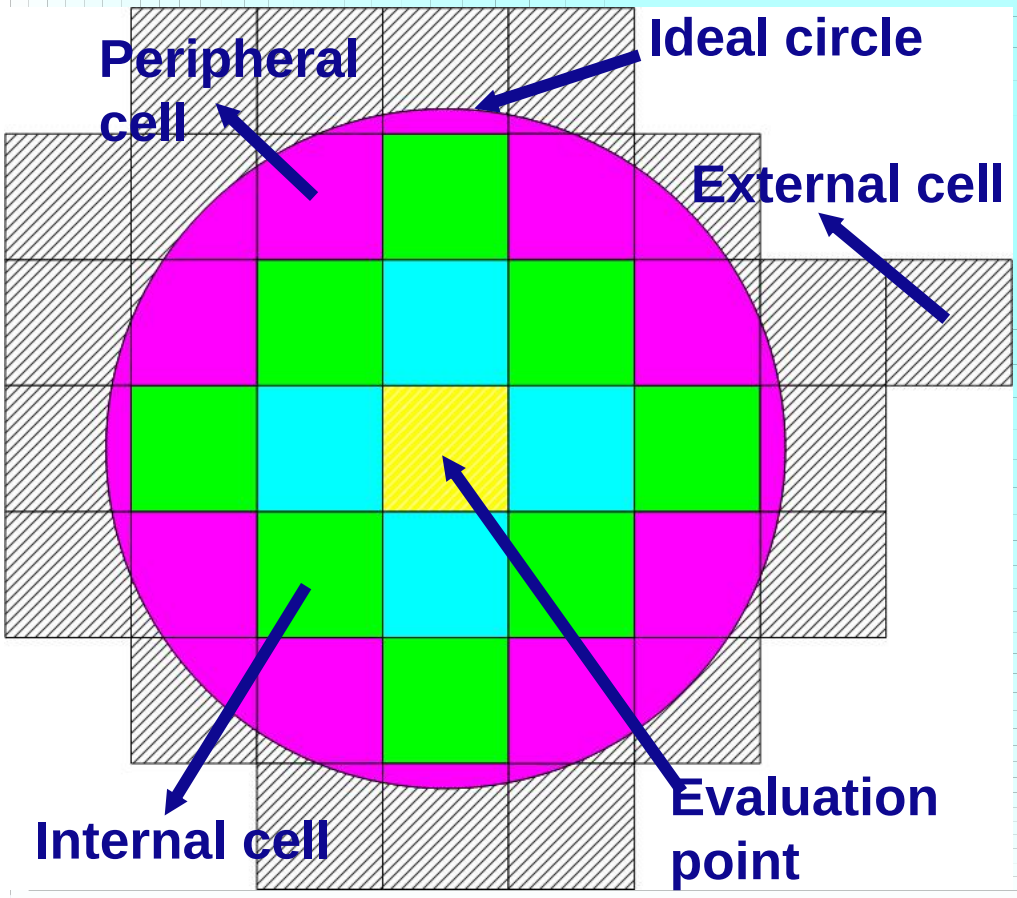
-They do not contravene any of the indications of international guidelines

-Cubical shapes give SAR values dependent on the reference system

-Contributions are unbalanced with respect to the evaluation points

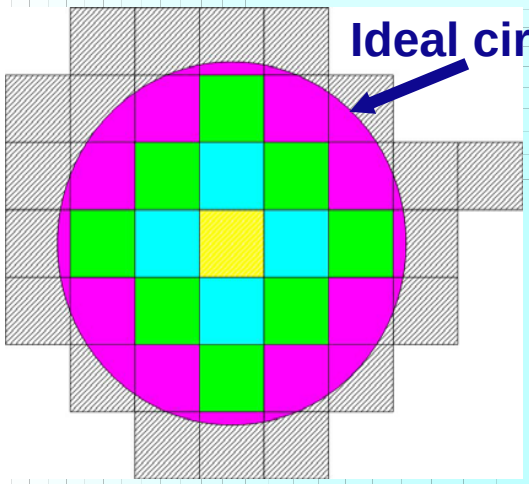
New Spherical Algorithms

Spherical shape <u>does NATURALLY select</u> the most close cells to the evaluation point.

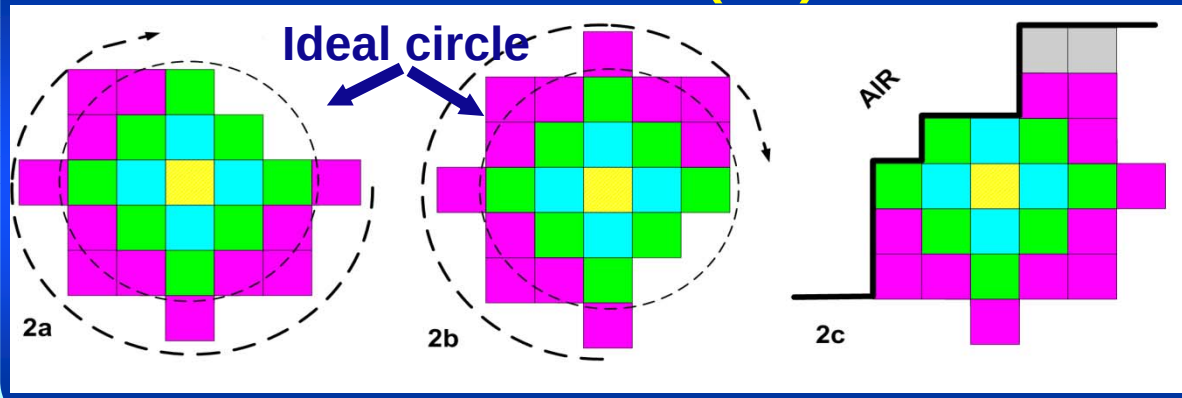


The Ideal Circle (sphere in 3D) is the circle centered in the evaluation point containing exactly *rm*. It classifies the cells as <u>Internal, External and Peripheral</u>. Internal cells are the "core" of the SAR evaluation. The contribution of peripheral cells should be proportional to the intersected area (volume). The kind of used approximation generates different algorithms.

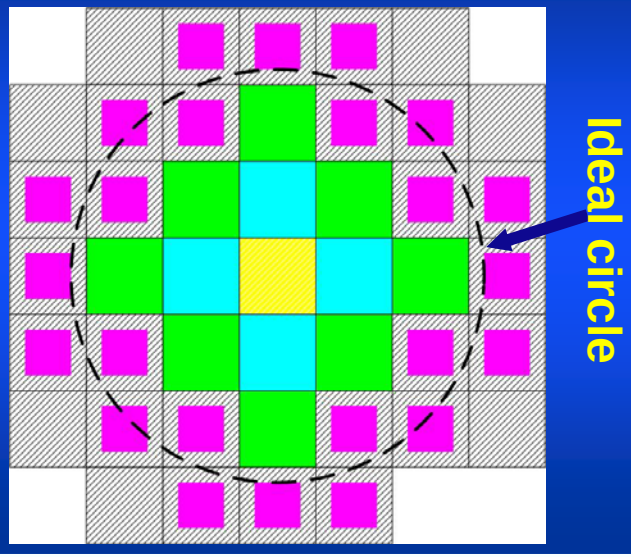
Spherical Algorithms



Onion Skin (OS)

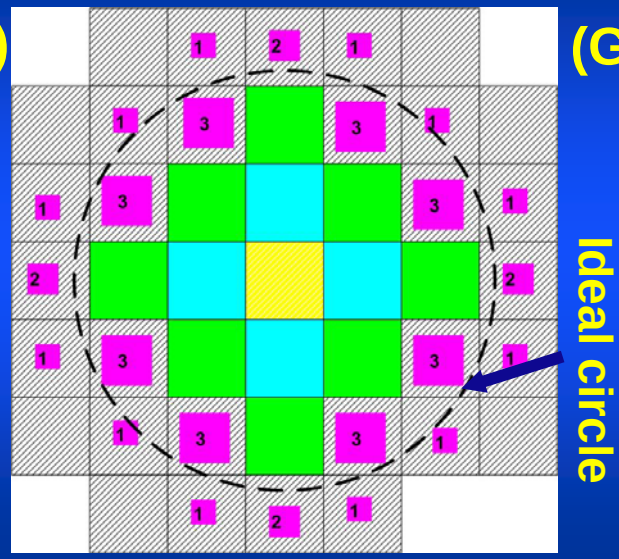


Graded Peripheral Cell (GPC)



Graded Peripheral Vertexes

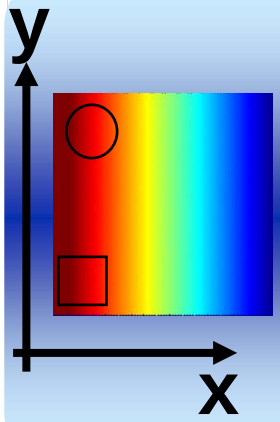
(GPV1) (GPV3)

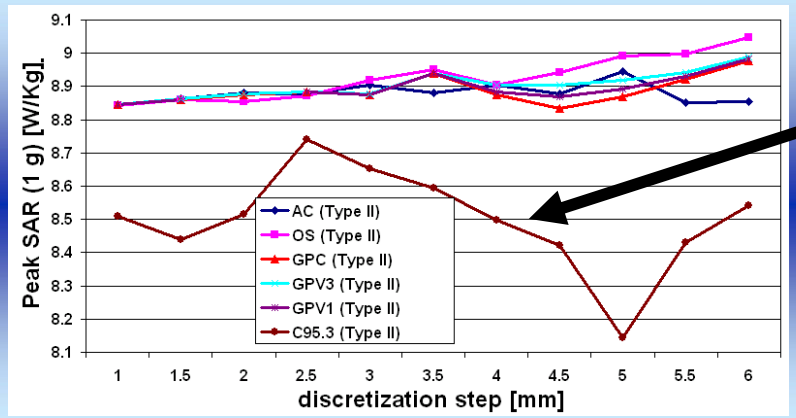


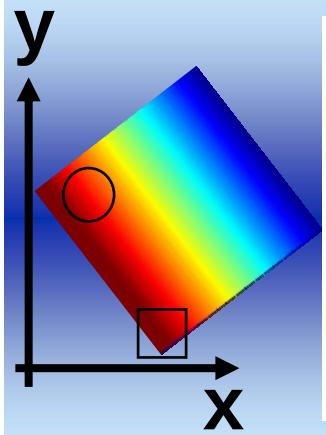
New Algorithms Vs Requirements

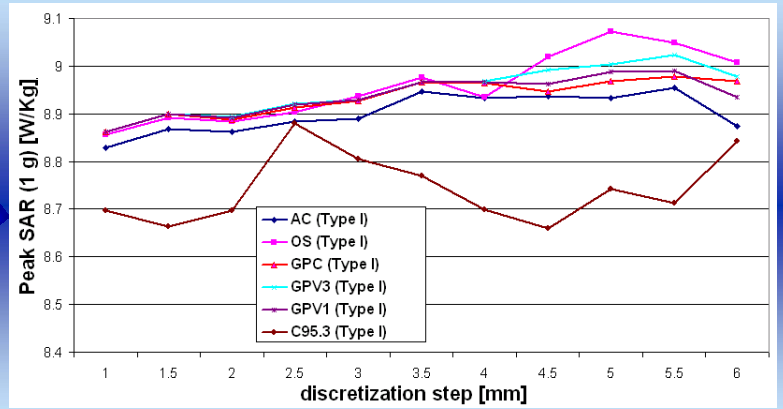
	Aver. Mass Toler. < 5%	*Independence on Ref. Syst.*	*Computability everywhere*	*Overall Accuracy*
FC	NO ☹	NO ☹	NO ☹☹	☹☹☹☹
FAC	YES ☺	NO ☹	NO ☹☹	☹☹
AC	YES ☺	NO 😐	YES ☺	😐
C95.3	NO ☹	NO ☹	YES 😐	☹☹☹☹
OS	YES ☺	YES ☺	YES ☺	☺
GPC	YES ☺	YES ☺☺	YES ☺	☺☺☺
GPV1	YES ☺	YES ☺☺	YES ☺	☺☺☺☺
GPV3	YES ☺	YES ☺☺	YES ☺	☺☺☺☺

Results: Peak SAR in test-cases









1) Unpredictable behaviour of the C95.3 algorithm: underestimation & wrong averaging mass.

2) Good agreement among GPC, GPV and GPV3 at various discretization steps.

3) Better attitude of spherical algorithms to deal with the problem: higher discrepancy among results obtained with cubical algorithms when the reference system is varied.

Dosimetry Application 3:
Reference Level Vs Basic Restriction

Exposure to uniform radio-frequency electromagnetic fields (RF-EM) can be assessed simply by measuring the electric and magnetic field strength or power density in one point occupied by the body (body removed) and comparing the results to the reference levels (ICNIRP).

Most exposure situations occur in the close vicinity of the source where the fields are more or less nonuniform. In this case, the maximal field strength may considerably exceed the reference levels for the external fields without exceeding the basic restrictions expressed in terms SAR.

Dosimetry Application 3: Reference Level Vs Basic Restriction

Table 4. Basic restrictions for time varying electric and magnetic fields for frequencies up to 10 GHz.[a]

Exposure characteristics	Frequency range	Current density for head and trunk (mA m^{-2}) (rms)	Whole-body average SAR (W kg^{-1})	Localized SAR (head and trunk) (W kg^{-1})	Localized SAR (limbs) (W kg^{-1})
Occupational exposure	up to 1 Hz	40	—	—	—
	1–4 Hz	$40/f$	—	—	—
	4 Hz–1 kHz	10	—	—	—
	1–100 kHz	$f/100$	—	—	—
	100 kHz–10 MHz	$f/100$	0.4	10	20
	10 MHz–10 GHz	—	0.4	10	20
General public exposure	up to 1 Hz	8	—	—	—
	1–4 Hz	$8/f$	—	—	—
	4 Hz–1 kHz	2	—	—	—
	1–100 kHz	$f/500$	—	—	—
	100 kHz–10 MHz	$f/500$	0.08	2	4
	10 MHz–10 GHz	—	0.08	2	4

Dosimetry Application 3: Reference Level Vs Basic Restriction

Table 6. Reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values).[a]

Frequency range	E-field strength ($V\ m^{-1}$)	H-field strength ($A\ m^{-1}$)	B-field (μT)	Equivalent plane wave power density S_{eq} ($W\ m^{-2}$)
up to 1 Hz	—	1.63×10^5	2×10^5	—
1–8 Hz	20,000	$1.63 \times 10^5/f^2$	$2 \times 10^5/f^2$	—
8–25 Hz	20,000	$2 \times 10^4/f$	$2.5 \times 10^4/f$	—
0.025–0.82 kHz	$500/f$	$20/f$	$25/f$	—
0.82–65 kHz	610	24.4	30.7	—
0.065–1 MHz	610	$1.6/f$	$2.0/f$	—
1–10 MHz	$610/f$	$1.6/f$	$2.0/f$	—
10–400 MHz	61	0.16	0.2	10
400–2,000 MHz	$3f^{1/2}$	$0.008f^{1/2}$	$0.01f^{1/2}$	$f/40$
2–300 GHz	137	0.36	0.45	50

@900 MHz

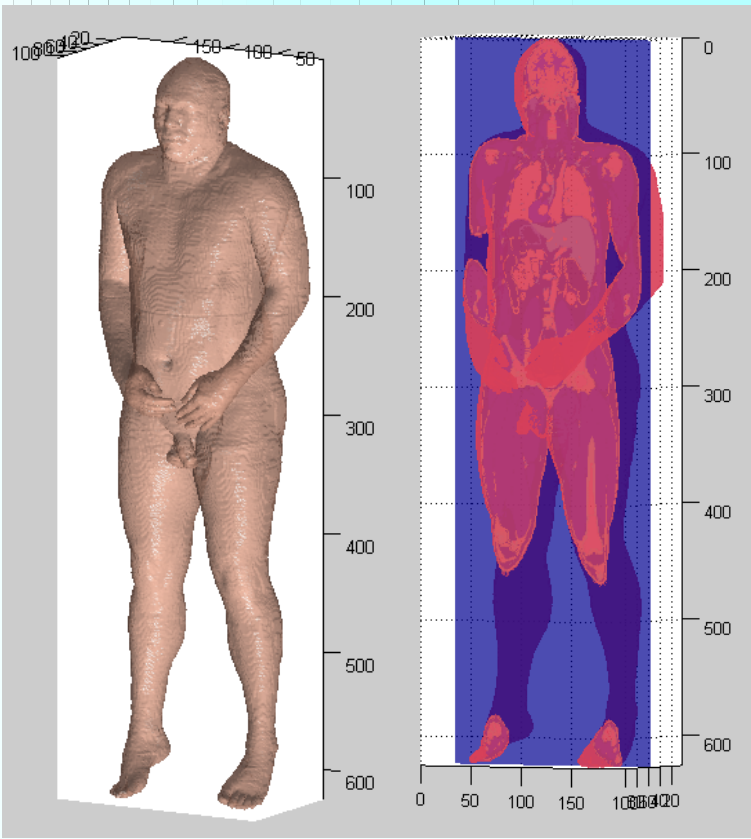
Reference Level: **Electric Field: 41 V/m**

Basic Restriction: **Whole Body SAR: 0.4 W/Kg**

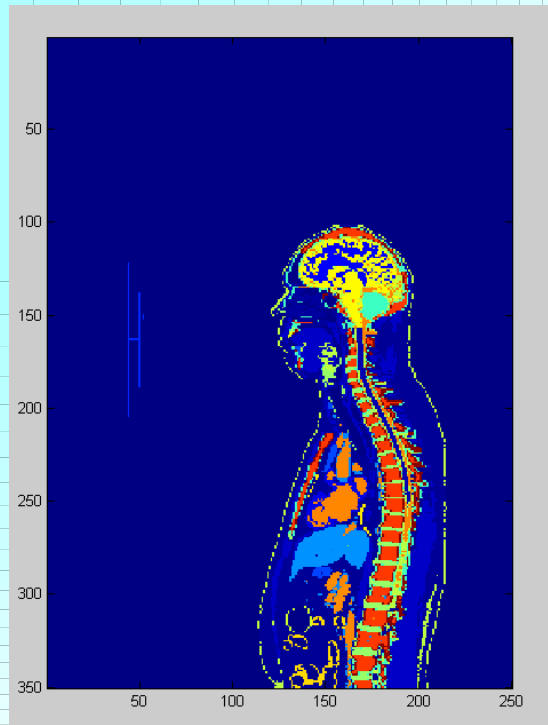
Localized SAR : 10 W/Kg

Dosimetry Application 3: Reference Level Vs Basic Restriction

Heterogeneous body model



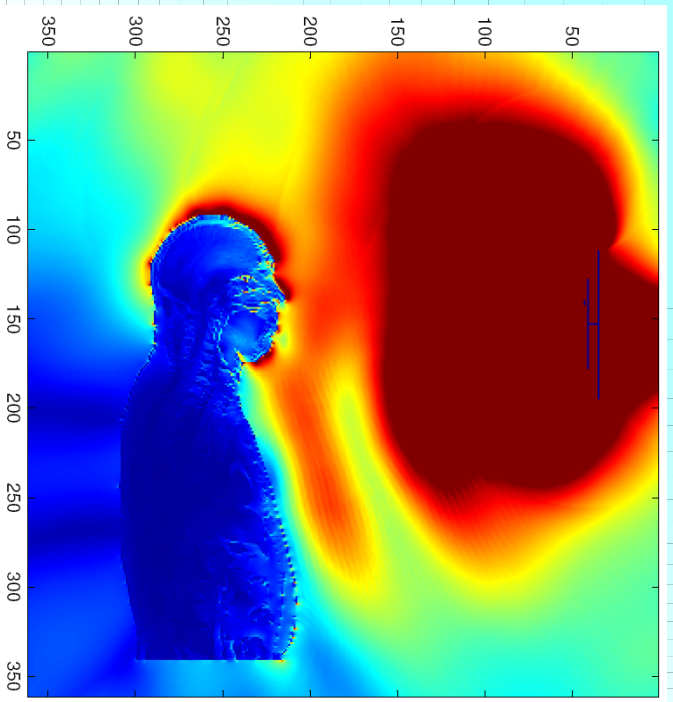
SIMULATION DOMAIN: UHF-RFID Antenna and Human Body



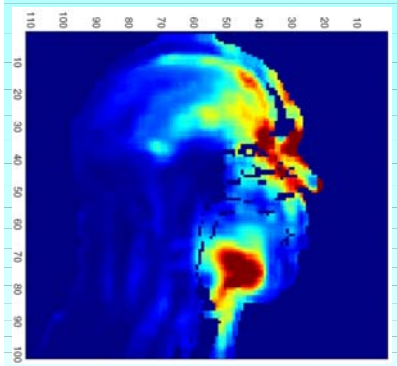
Dosimetry Application 3: Reference Level Vs Basic Restriction

- ***Distance: 50 cm***

Distance [m]	Electric Field [V/m]
0.5	25.3
1.0	13.7
1.5	10.9
2.0	6.3



SAR



SAR

ALG	SAR 1g [W/Kg]	SAR 10g [W/Kg]
C95.3	0.133	0.059
Ad.cube	0.169	0.062
O. Skin	0.175	0.062

CONCLUSIONS

Numerical dosimetry has been used in order to solve three different and complicated dosimetric problems:

-Exposure of different numerical phantom to EM fields
-Numerical evaluation of SAR by using different algorithms
-Comparison between Basic restriction and Reference levels

In all cases, the interpretation of the results is not trivial and requires adequate EM skill and competences. EU Directive should contemplate the use of simplified models suitable for non-expert Employers.