

*Current Trends in Health & Safety Risk Assessment
of Work-Related Exposures to EMFs*

14-16 February 2007, Milan, Italy

**Uncertainty in Numerical Dosimetry
in the Radiofrequency Range**

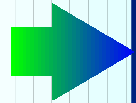


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Outline



Rationale and goals

SAR & RF Safety Guidelines

Commonly used SAR Algorithms

Alternative SAR Algorithms

Conclusions and Firing Questions

Goals

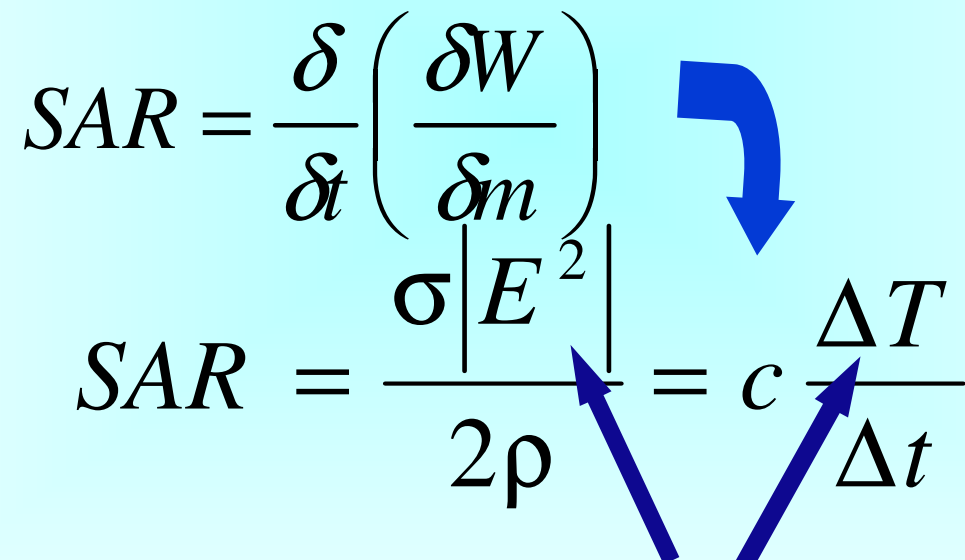
-To open a constructive discussion about the opportunity of a standardization of the technique for the dosimetric parameter numerical evaluation.

-To demonstrate the incomparability of dosimetric parameter values obtained through different (formally correct) algorithms.

-To discuss new possible strategies.

Specific Absorption Rate

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.

$$SAR = \frac{\delta}{\delta t} \left(\frac{\delta W}{\delta m} \right)$$
$$SAR = \frac{\sigma |E|^2}{2\rho} = c \frac{\Delta T}{\Delta t}$$
The diagram shows the derivation of SAR. The first equation is SAR = delta/delta t (delta W / delta m). A blue arrow points from this equation to the second equation, SAR = (sigma |E|^2) / (2*rho) = c * (delta T / delta t). The second equation is split into two parts: (sigma |E|^2) / (2*rho) and c * (delta T / delta t). A blue arrow points from the first part to the second part, indicating the relationship between the two forms.

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.

Specific Absorption Rate

Three different SAR are often used:

Whole Body SAR

10g-SAR

1g-SAR

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

$$SAR_{10g} = \frac{\int_{V(10g)} \sigma |E|^2 / 2 \, dv}{\int_{V(10g)} \rho \, dv}$$

$$SAR_{1g} = \frac{\int_{V(1g)} \sigma |E|^2 / 2 \, dv}{\int_{V(1g)} \rho \, dv}$$

discretization

$$SAR_{rm} = \frac{\int_{V(rm)} \sigma |E|^2 / 2 \, dv}{\int_{V(rm)} \rho \, dv} \longrightarrow SAR_{rm} = \frac{\sum_{i \in \bar{V}(rm)} (\sigma_i |E_i|^2 / 2) \Delta V_i}{\sum_{i \in \bar{V}(rm)} \rho_i \Delta V_i}$$

rm=reference mass; V(rm)=Volume containing rm

Specific Absorption Rate

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

Although the shape of the volume containing the reference mass does not affect the divisor, its impact on the SAR could be relevant; the distribution of the electric field varies greatly from point to point inside the tissues, so that the use of different volumes could generate strong discrepancies.

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?

Do the major RF safety guidelines give any suggestion in order to deal with such issues?

IEEE Standard C95.1 - 2006

In IEEE standard, attention is paid to the rigorous definition of the limits (pinnae limits have been added in the last version) whilst nothing but volume-shape (cubical) is defined for the SAR calculation.

Table 6—BRs for frequencies between 100 kHz and 3 GHz

		Action level ^a SAR ^b (W/kg)	Persons in controlled environments SAR ^c (W/kg)
Whole-body exposure	Whole-Body Average (WBA)	0.08	0.4
Localized exposure	Localized (peak spatial-average)	2 ^c	10 ^c
Localized exposure	<u>Extremities^d and pinnae</u>	4 ^c	20 ^c

^aBR for the general public when an RF safety program is unavailable.

^bSAR is averaged over the appropriate averaging times as shown in Table 8 and Table 9.

^cAveraged over any 10 g of tissue (defined as a tissue volume in the shape of a cube).*

^dThe extremities are the arms and legs distal from the elbows and knees, respectively.

*The volume of the cube is approximately 10 cm³.

ICNIRP Guidelines - 1998

In ICNIRP Standard, only the reference mass is imposed. Neither the volume shape nor any procedure for the SAR calculation are given.

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/ <i>f</i>	—	—	—
	4 Hz–1 kHz	10	—	—	—
	1–100 kHz	<i>f</i> /100	—	—	—
	100 kHz–10 MHz	<i>f</i> /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/ <i>f</i>	—	—	—
	4 Hz–1 kHz	2	—	—	—
	1–100 kHz	<i>f</i> /500	—	—	—
	100 kHz–10 MHz	<i>f</i> /500	0.08	2	4
	10 MHz–10 GHz	—	0.08	2	4

^a Note:

1. *f* is the frequency in hertz.
2. Because of electrical inhomogeneity of the body, current densities should be averaged over a cross-section of 1 cm² perpendicular to the current direction.
3. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ (~1.414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.
4. For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate basic restriction.
5. All SAR values are to be averaged over any 6-min period.
6. Localized SAR averaging mass is any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure.

SAR Algorithms

Few information in Safety Standards



Different choices → different algorithm strategies

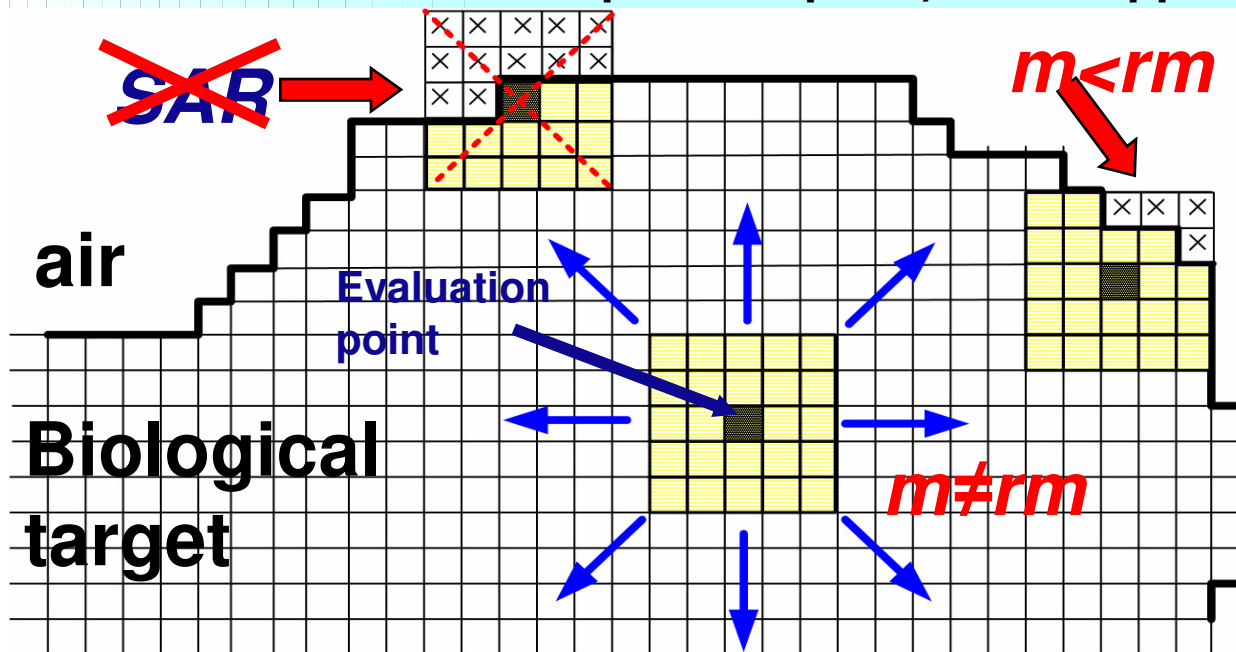
Does it mean “different SAR values”?




Overview on the commonly used SAR algorithms

Fixed-Cube Algorithm

One approach computes the SAR on a certain point by considering the contributions of the cells which belong to a fixed cubical volume (the volume is the same for each computation point) which approximately contains rm .



Easiness 

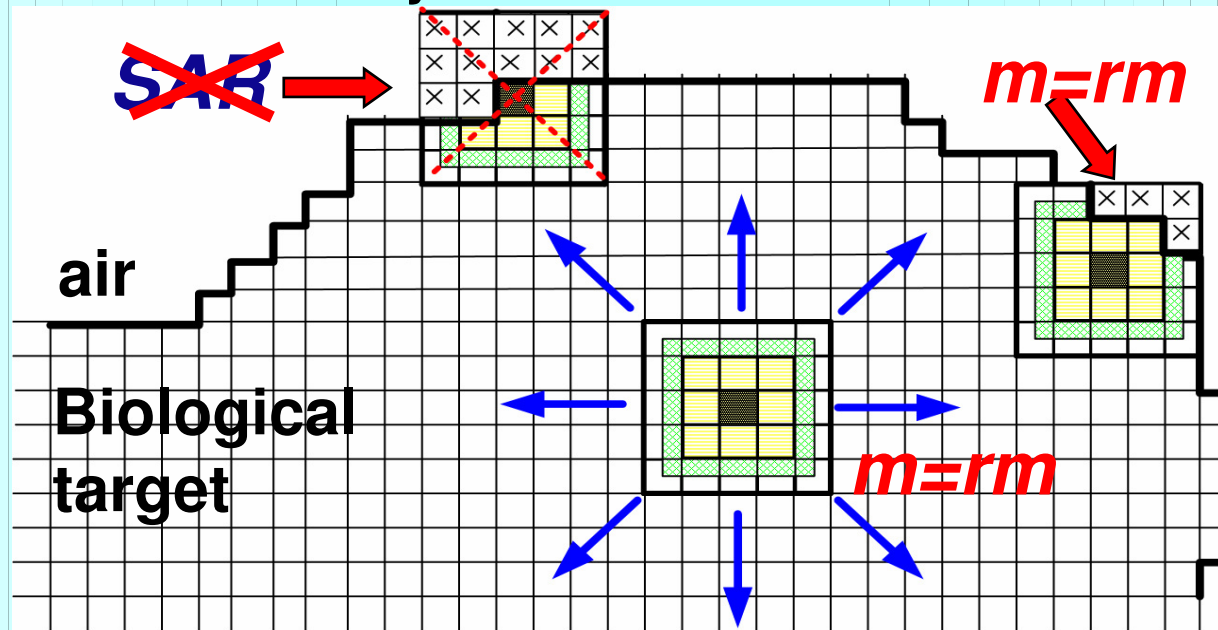
Depending on the discretization step, it is often impossible to reach exactly rm using a cube. Some authors use parallelepipeds. 

The non modifiability of the volume shape causes SAR evaluation in presence of air $\rightarrow m < rm$ 

A maximum percentage of air imposed: if the limit is exceeded, SAR remains undetermined. But in the most external points high SAR values are found! 

Fixed-Adjustable-Cube Algorithm

A first improvement of the previous technique uses a cubic volume dynamically adjusted in order to consider exactly rm . A maximum percentage of air is tolerated. A sequence of successive cubes is built up till a mass $>rm$ is reached. The last cube with mass $<rm$ is the core. Only a portion of the last layer is considered so that $m=rm$ is reached.



Limit of this algorithm: the incapability to determine the SAR in points closed to the surface of the exposed target;

C95.3 Algorithm

IEEE Std C95.1™-2006



IEEE Std C95.3™-2002

**IEEE Recommended Practice for
Measurements and Computations of Radio
Frequency Electromagnetic Fields With
Respect to Human Exposure to Such Fields,
100 kHz–300 GHz**

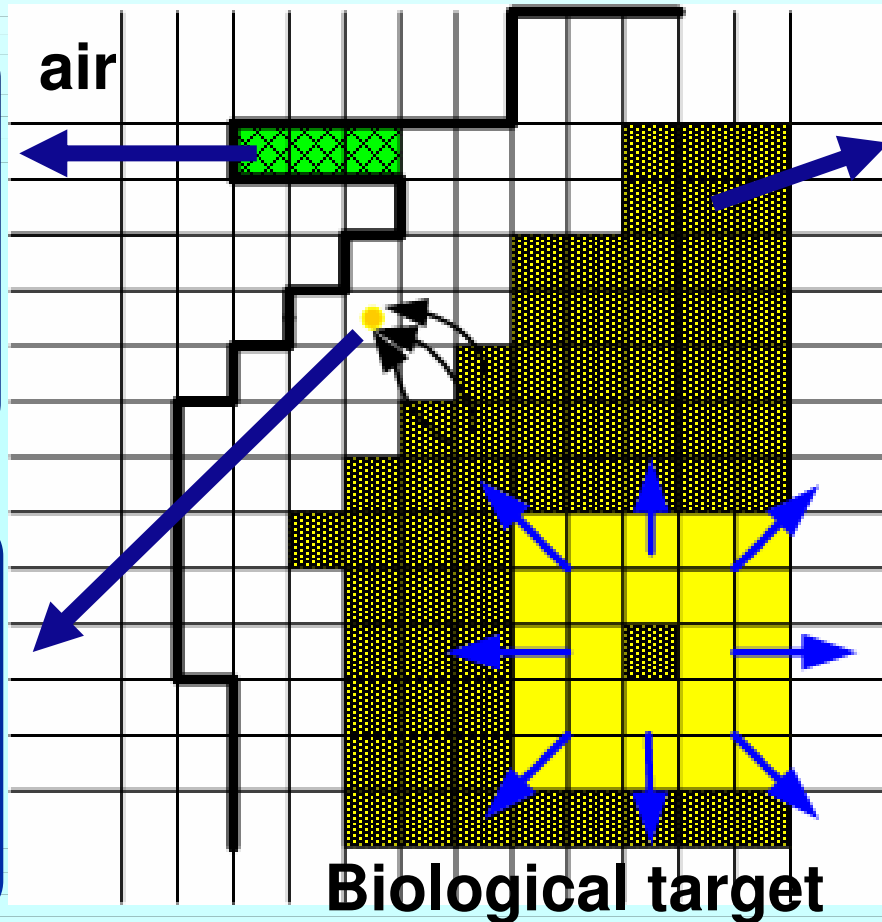
C95.3 Algorithm

Phase 3: extended cube

A new cube is used, containing both air and tissues, expanded until r_m is reached.

Phase 2: Maximum

These points are assigned the highest average SAR of the averaging volume in which they are enclosed



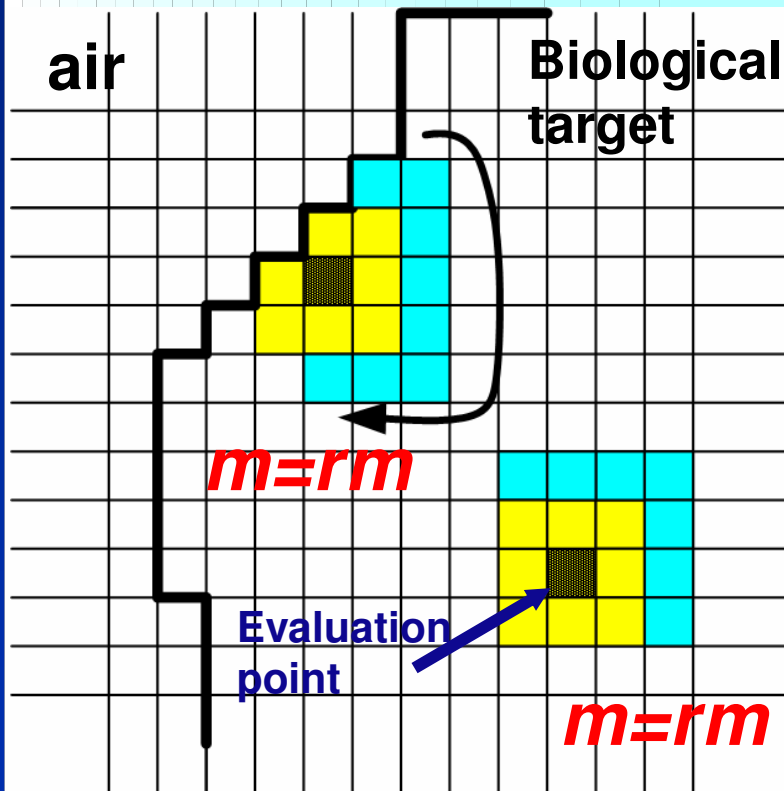
Phase 1: Fixed-cube

Whenever a fixed cube containing only tissue exists, the fixed cube strategy is applied. All the points for which the phase 1 cannot be applied are marked and will be processed during the phase 2.

Limit of this algorithm: strong discontinuities when different phases are used. → SATURATION

Adaptive-Cube (AC) Algorithm

In the AC Algorithm, the cubical shape is not indispensable; cells are assembled around the evaluation point by following established criteria and excluding air. The insertion of new cells ends when the total mass is equal to rm . The shape of the volume is given by the set of cells which better approximate a cube intersected with non-tissue points.



SAR is evaluated over a mass equal to rm and computation is performed in each point of the biological target, including the most external ones.

Preliminary Discussion

The comparison among the presented numerical techniques is not possible because some algorithms do not evaluate the SAR everywhere.

Even radically different algorithms can comply with the few indications reported in RF safety guidelines, despite it is easily predictable that they could generate discrepant results! Need of standardization.

Is the AC algorithm the best one? Does it depend on the volume-building strategy?

The Best Shape

- 1) Cubical shapes give SAR values which depend on the chosen reference system.
- 2) Cubical shapes select contributions unbalanced with respect to the evaluation points.

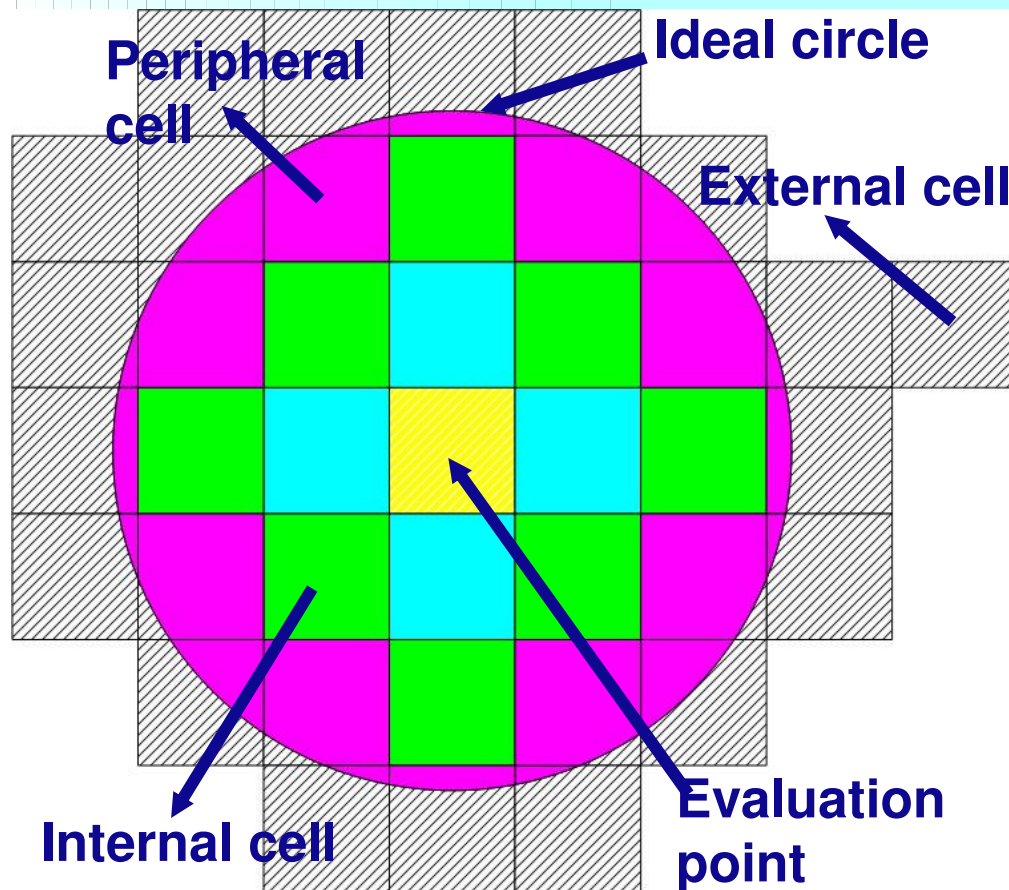
What is the best shape of the reference mass?

POSSIBLE PROPOSAL:

$V(r_m)$ = the volume V containing the portion of continuous tissue as large as r_m which is as close as possible to the evaluation point.

New Spherical Algorithms

Spherical shape does NATURALLY select the most close cells to the evaluation point.



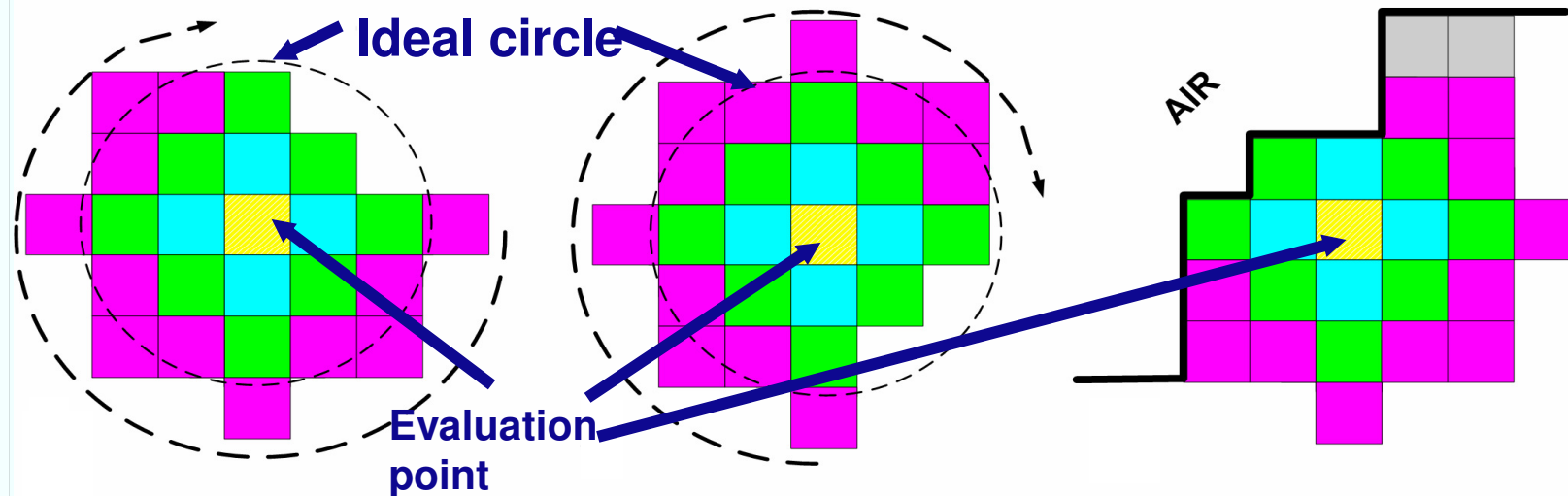
The Ideal Circle (sphere in 3D) is the circle centered in the evaluation point containing exactly rm . It classifies the cells as Internal, External and Peripheral. Internal cells are the “core” of the SAR evaluation. The contribution of peripheral cells should be proportional to the intersected area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


Onion Skin Algorithm


The strategy gives the name (onion skin) to the algorithm: if the mass contained in a sphere of radius r (onion) is inferior to " rm ", new cells are added selecting them out among those belonging to the layer with radius $r+1$ (skin). When " rm " is reached, the volume is found.

The volume contains a mass equal to rm 

SAR can be evaluated everywhere in the target 



Volume is unbalanced respect to the eval. point 

Not-uniqueness of the peripheral cell selection 

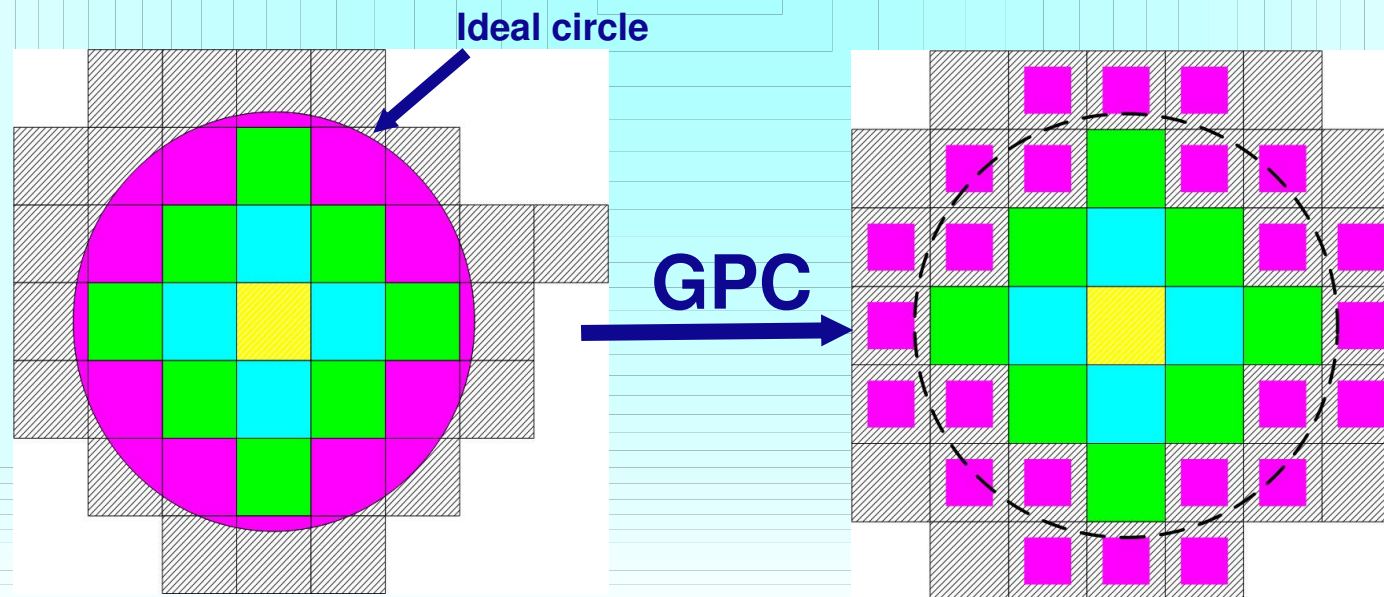
Graded Peripheral Cell Algorithm

The Graded Peripheral Cells (GPC), considers an equal fraction of all the peripheral cells, regardless to the effective volume individuated by the ideal circle. The difference among the mass of the internal cells and “ r_m ” is computed and equally subdivided among all of the peripheral cells

volume perfectly balanced
and uniqueness of the
peripheral cell selection

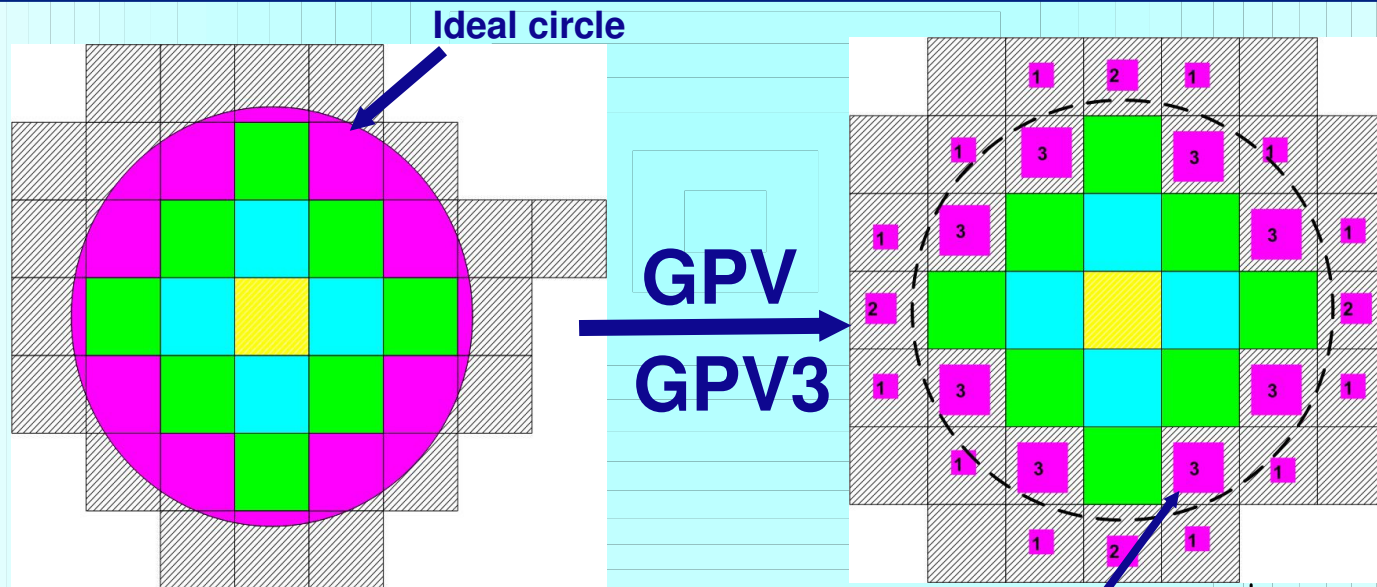


Cells with smaller
intersection give the same
contribution



Graded Peripheral Vertex Algorithms

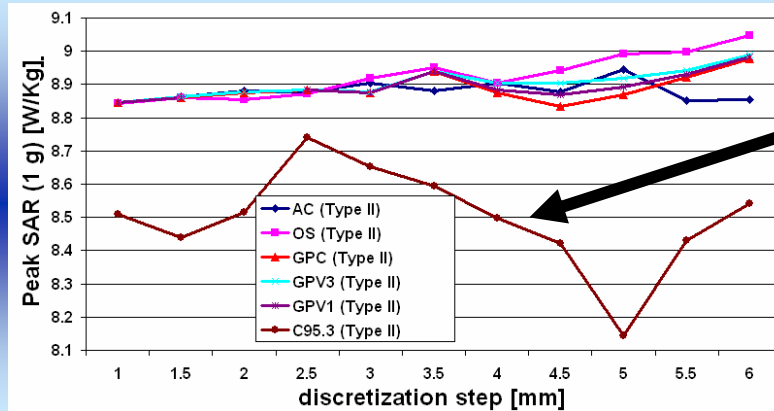
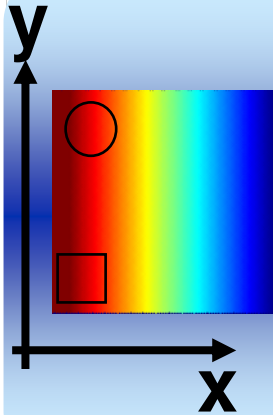
The Graded Peripheral Vertex (GPV) and Vertex-3 (GPV3) algorithms, evaluate the number of vertexes intersected by the ideal circle. Such a number is used for discriminating how much of a cell is internal to the circle. GPV calculates the SAR contribution proportionally to the number of internal vertexes. GPV3 proportionally to the cube of the internal vertexes.



$$mass_{i^{th_cell}} = \frac{(rm - Internal_mass)}{\sum_{j \in peripheral_cells} (vertexes_j)^\alpha} \cdot (vertexes_i)^\alpha$$

$\alpha=1(GPV)$
 $\alpha=3(GPV-3)$

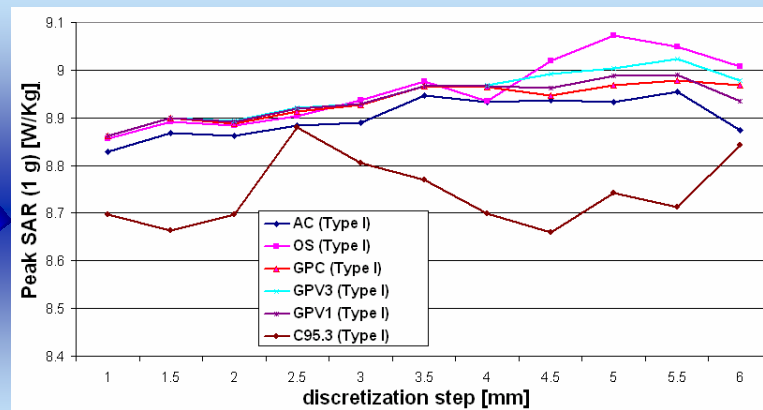
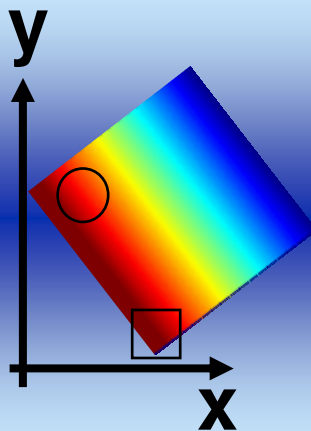
Results: Peak SAR in test-cases



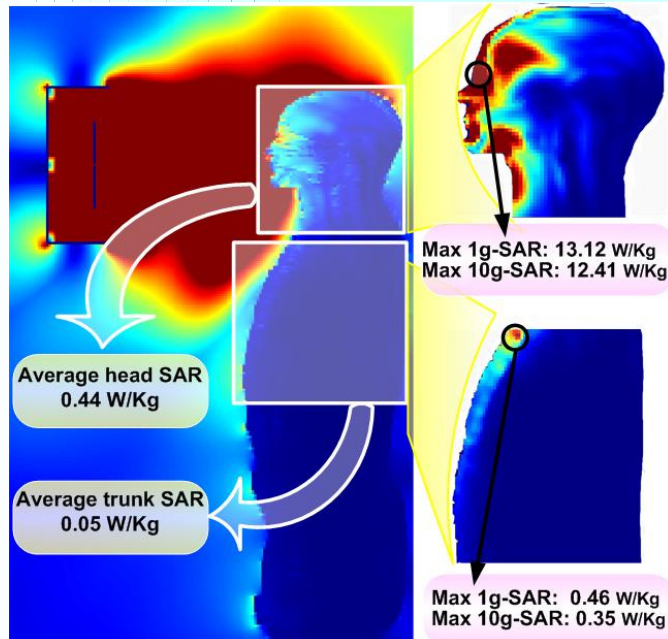
1) Unpredictable behaviour of the C95.3 algorithm: underestimation & wrong averaging mass.

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.



Results: Human-Antenna Problem



Application to Human-Antenna problems

-Only 5 Algorithms have been compared. The others do not allow the SAR evaluation in every point.

-Where computable, peak SAR values are substantially the same. This was expected, as the peak is found close to the human surface → high E values in an appreciable region.

-In superficial points, because of the deformation of the volume, the refinement strategies are unappreciable

Peak SAR comparison

SAR Algorithm	Peak SAR (1g)	Peak SAR (10g)
Adaptive Cube (AC)	27.93	14.39
Onion Skin (OS)	27.00	14.32
Graded Peripheral Cell (GPC)	27.65	14.73
Graded Peripheral Vertex (GPV)	27.89	14.78
Graded Peripheral Vertex-3 (GPV3)	28.03	14.85

Results: Average and Max Difference

Percentage Difference				
SAR Algorithm	SAR (1g)		SAR (10g)	
	Average %	Maximum %	Average %	Maximum %
AC versus GPV3	8.43	99.08	5.12	69.95
OS versus GPV3	6.90	95.39	3.31	53.71
GPC versus GPV3	4.93	90.14	0.14	3.04
Graded Peripheral Vertex (GPV)	2.66	42.89	0.08	2.33
Graded Peripheral Vertex-3 (GPV3)	---	---	---	---

GPV3 Vs (AC,OS,GPC,GPV): SAR values are compared in each target point both for $rm=1g$ and $rm=10g$. Two parameters are reported: Percentage Average Difference and Percentage Maximum Difference.

-by improving the accuracy of the algorithms, differences decrease

-Difference referred to the 10g cases are inferior to the 1g cases (as expected).

-Maximum Percentage Difference: almost 95% between OS and GPV3 (1g). Similar algorithms (GPV and GPV3) give differences up to 43% in some investigated points!

Conclusions & Firing Questions

Some commonly used algorithms have been examined. Even though they do not contravene any of the guidelines, they give different SAR values.

New algorithms have been proposed in order to progressively improve the accuracy of the SAR evaluation. In some cases, differences are quite impressive.

Firing Questions

Should the algorithm for the SAR evaluation be standardized?

If so, which is the best shape for the volume containing the reference mass?