5th International Workshop on
Biological Effects of Electromagnetic Fields

September 28th - October 2nd 2008, Città del Mare, Terrasini, Palermo

COMPLIANCE WITH EU BASIC RESTRICTIONS NEAR INDUCTION FURNACES USED IN PRECIOUS METAL INDUSTRY: A 3D NUMERICAL DOSIMETRIC ANALYSIS USING THE SCALAR POTENTIAL FINITE DIFFERENCE (SPFD) TECHNIQUE AND A POSTURABLE DIGITAL BODY MODEL

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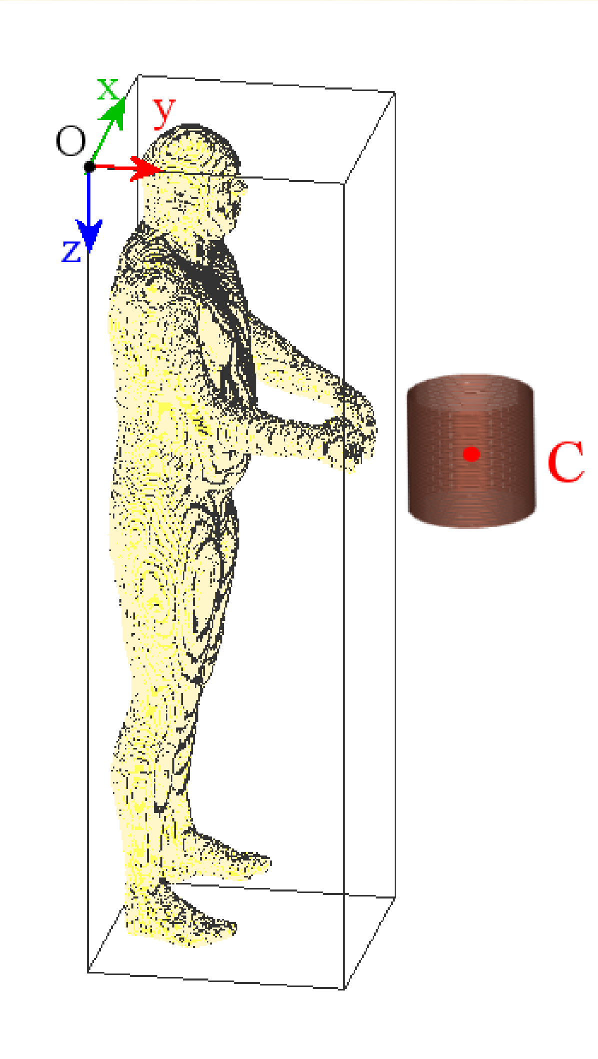
Summary

Verifying the compliance of exposure limit values for current densities implies different sequential steps. The example of a man working near an induction furnace used in gold industry is presented here:

1. Building the “exposure scenario”
2. Modelling the exposed subject (posture)
3. Modeling the source
4. Calculating the current density
5. Post-processing (surface averaging, limitation to CNS tissues)
6. Result analysis

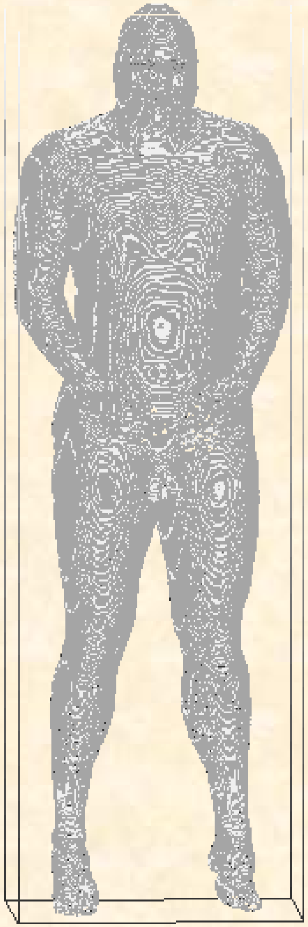
Exposure scenario



- Used in the gold industry
- **Magnetic field only**
- F = 3450 Hz
- I = 400 A
- Monophase source

- Cx=0,3m Cy=0,75m Cz=0,75m
- Radius= 0,09m
- The edge of the fingers are less then 10 cm distant from the conductors

Reference voxel phantom: VHP body model

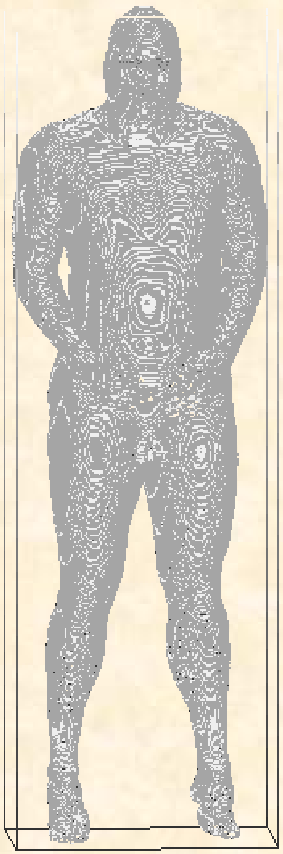


Model	nx	ny	nz	n_cells	Model memory occupation [Mb]
Head 1mm	178	235	211	8826130	8.42
Man 3mm	196	114	626	13987344	13.34
Man 2mm	293	170	939	46771590	44.60
Man 1mm	586	340	1878	374172720	356.84

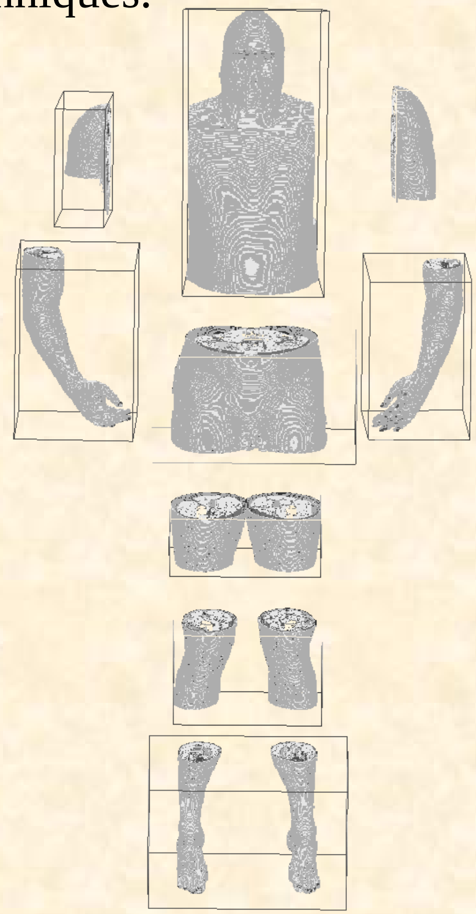
The reference voxel phantom is the VHP model of the entire body at 3mm resolution. With that choice the dosimetric problems can be solved with standard PC. With higher resolutions, problems may arise regarding both calculation time and memory resources demand.

Articulation algorithm: subdivision in portions

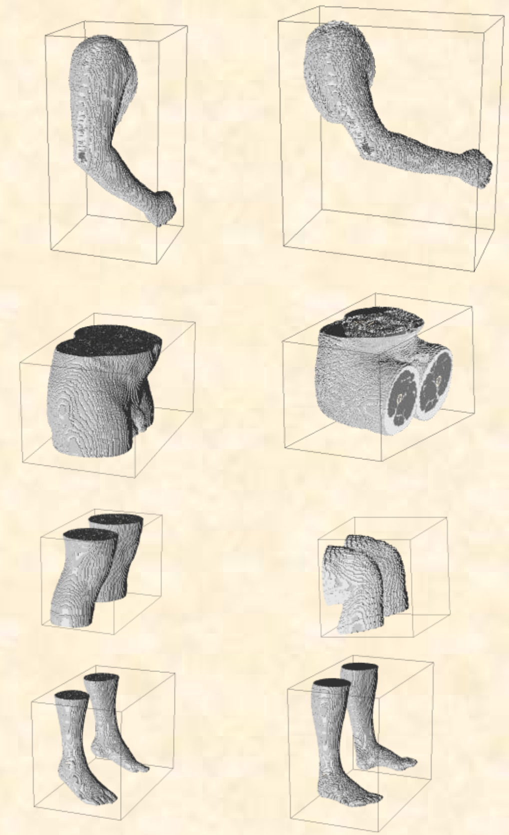
Vhp models represent the human body in standing posture and cannot be directly used for dosimetric evaluations in different postures, as required by occupational exposure studies. An articulation algorithm is presented that is particularly suited for use in conjunction with finite difference calculation techniques.



Model at rest



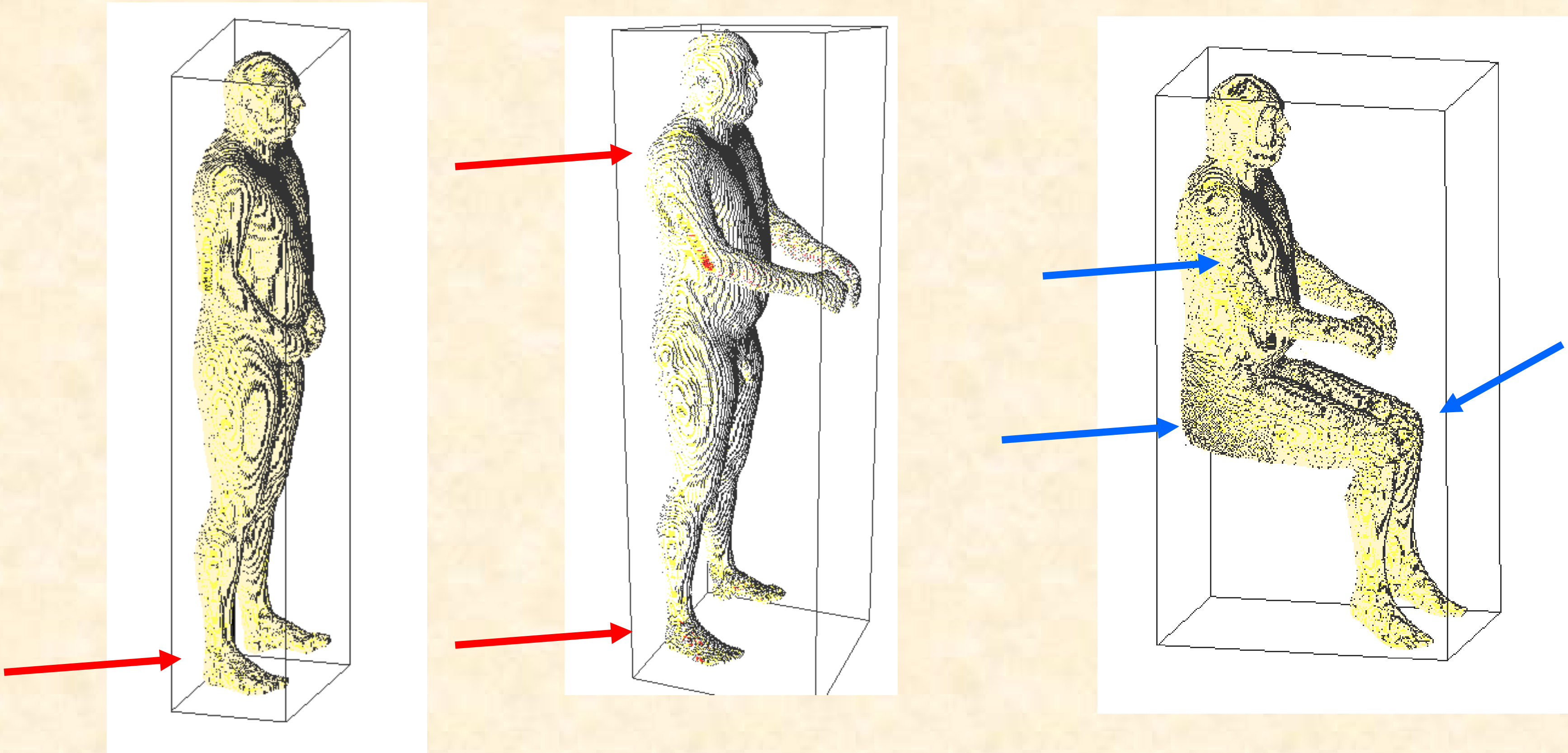
Subdivision in portions



Articulation of the single portions

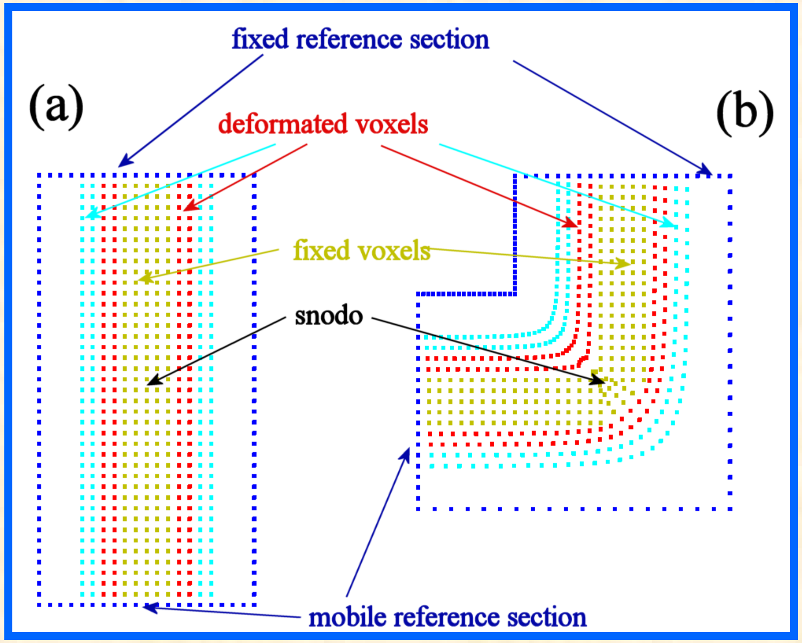
Articulated voxel phantoms

The articulated portions are re-assembled together with the others (translated and/or rotated) to compose the articulated voxel phantom



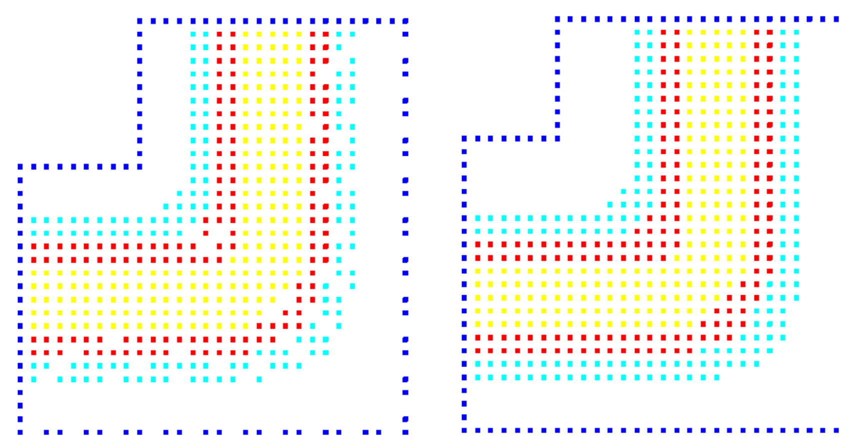
Models used in the examples showed in this presentation

Elastic model



An elastic model is built which separates voxels that undergo rigid translations and rotations (bones for example) and voxels that go through elastic deformations (fleshy parts).

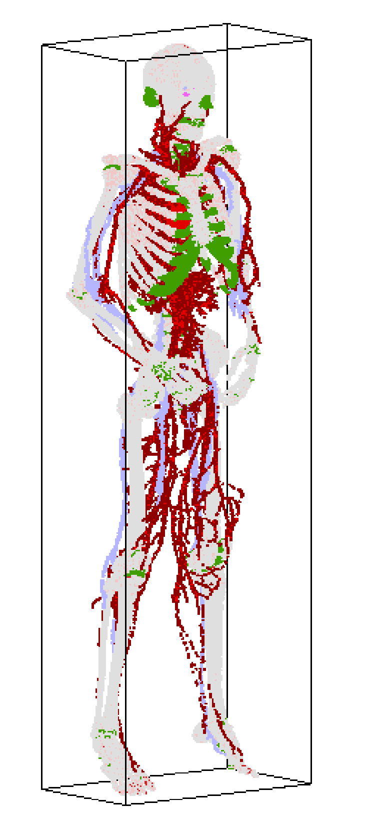
The articulation process deforms the voxels close to the joints, so that the articulated body model has to be **resampled** over a regular grid before it can be used as a base for finite difference calculations.



Resampling in two steps

Checks on articulated models

- Tissue continuity → blood vessels, nerves
- Mass conservation → critical in conjunction with the resampling step (+0,4 kg in the presented case)

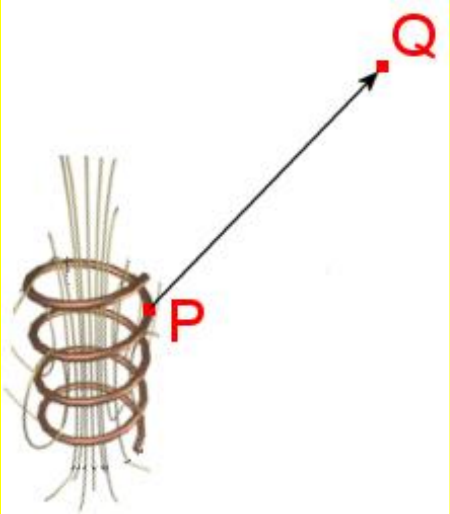


Modeling the source

- Based on the numerical integration of Laplace law
- Solenoid dimensions (diameter, length) are taken from manufacturer's specifications
- Coil current is in agreement with manufacturer's electrical data (voltage, power)
- Current x turn product and coil exact position in the apparatus are adjusted to fit experimental data

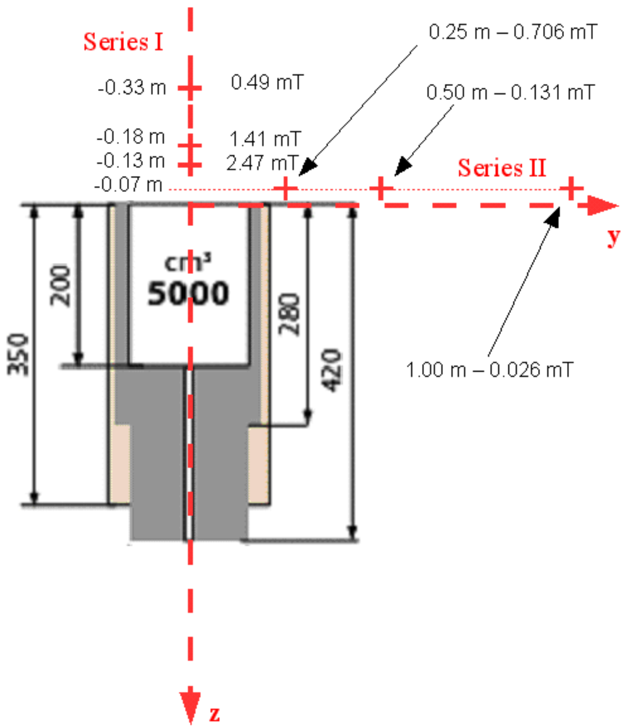
Here I is the coil current, Q is the point where fields are computed, Γ is the coil path and P is a generic point along it

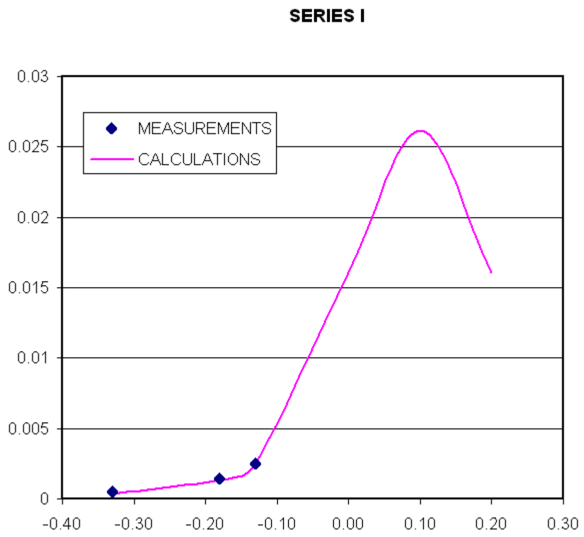
$$\mathbf{B}(Q) = \frac{\mu_0 I}{4\pi} \int_{P\in\Gamma} \frac{\mathbf{dP}\times(\mathbf{Q}-\mathbf{P})}{|\mathbf{Q}-\mathbf{P}|^3} \qquad \mathbf{A}(Q) = \frac{\mu_0 I}{4\pi} \int_{P\in\Gamma} \frac{\mathbf{dP}}{|\mathbf{Q}-\mathbf{P}|}$$

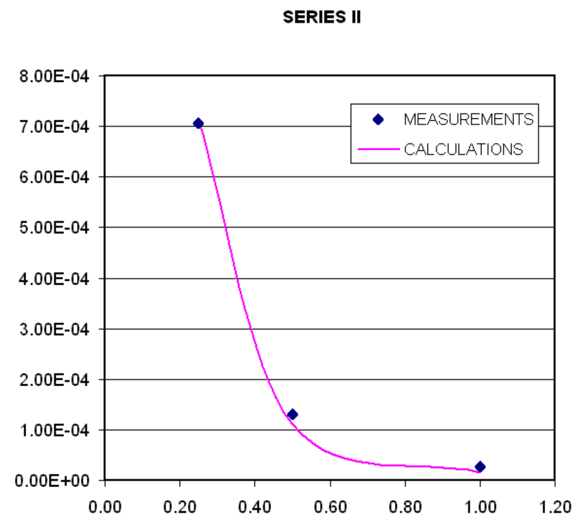


Modeling the source (cont.)

Measurement setup and results







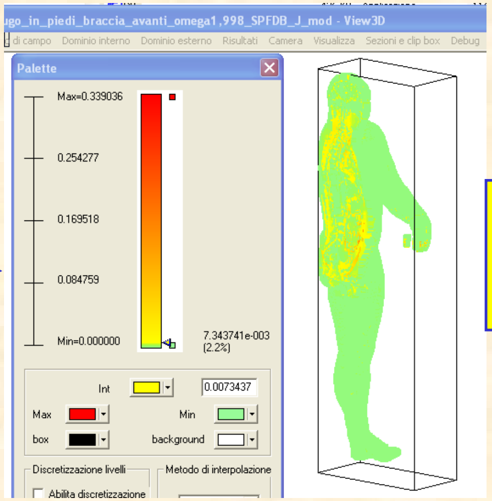
Layout of the numerical analysis

Field distribution in the body model volume

σ

SPFD

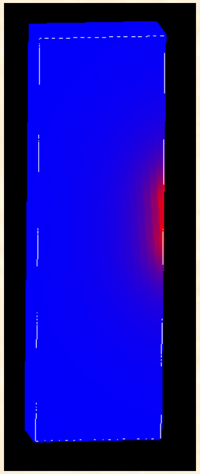
$$\Phi_{n0} = \left(\frac{1}{\sum_{i=1}^{6} \bar{\sigma}_{mi}} \right) \cdot \sum_{i=1}^{6} \left\{ \bar{\sigma}_{mi} \left[\Phi_{ni} - (-1)^{i} j\omega l_c A_{mi} \right] \right\}$$

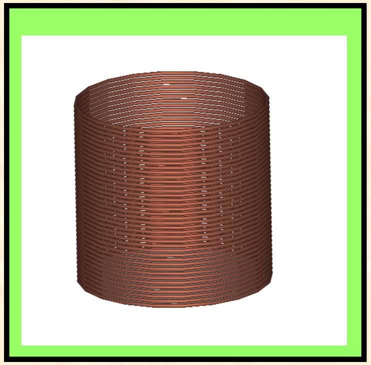


$\left| \vec{J}_{peak} \right|$

$\vec{A}$

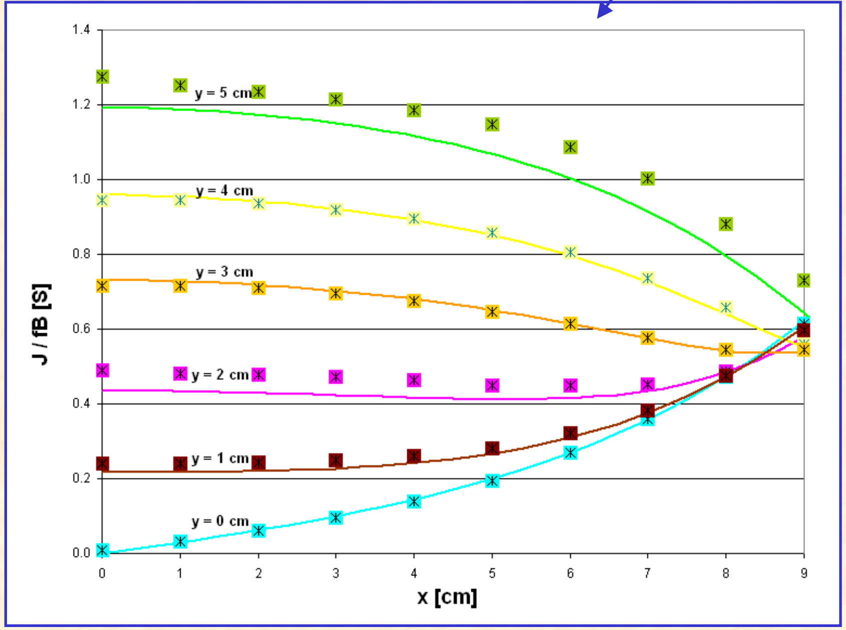
Coil model

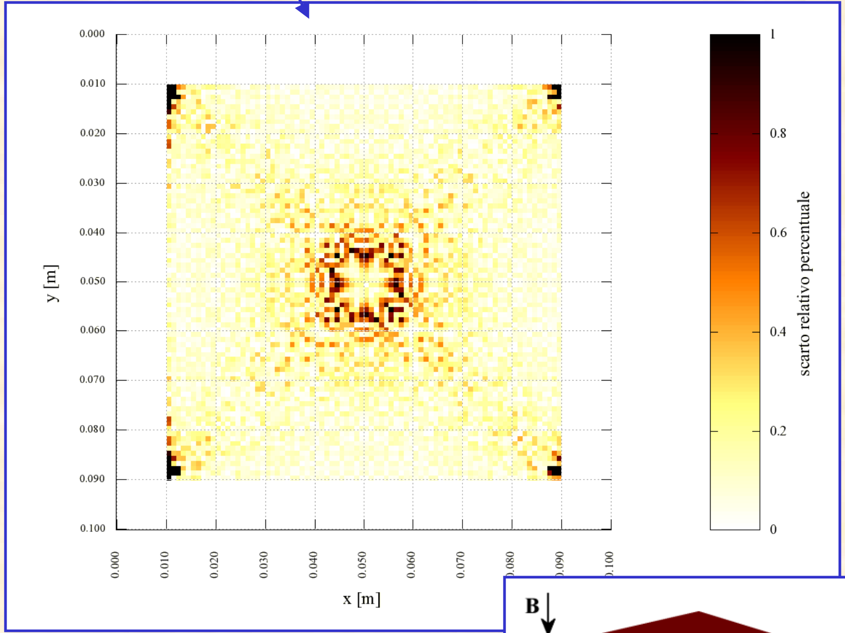


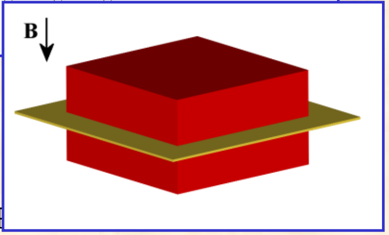


Numerical method and application

- Based on the Scalar Potential Finite Difference method (SPFD)
  - scalar method also in 3D problems
  - no additional boundary conditions solving the magnetic problem
  - only the conductive cells are considered not the empty space in the box containing the model)
- Validated with experimental data and analytical models





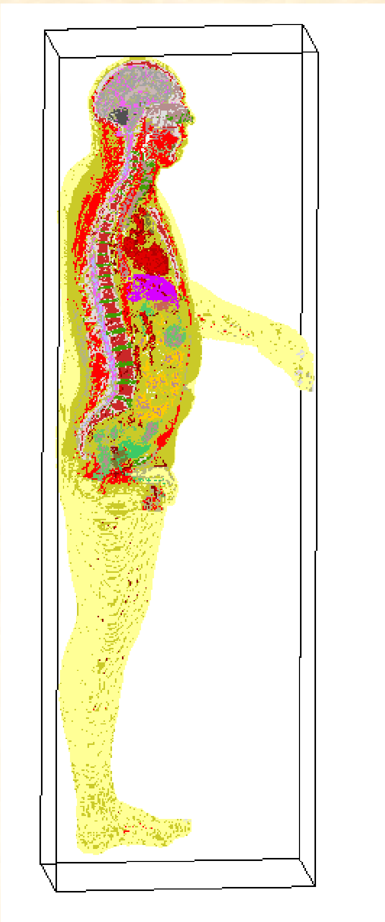


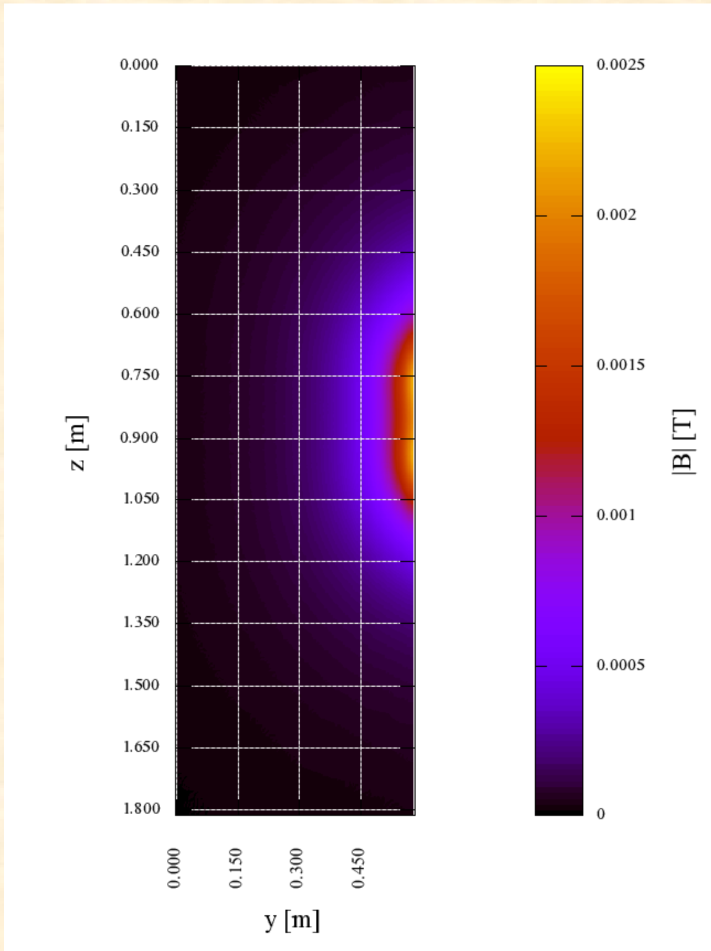
B field

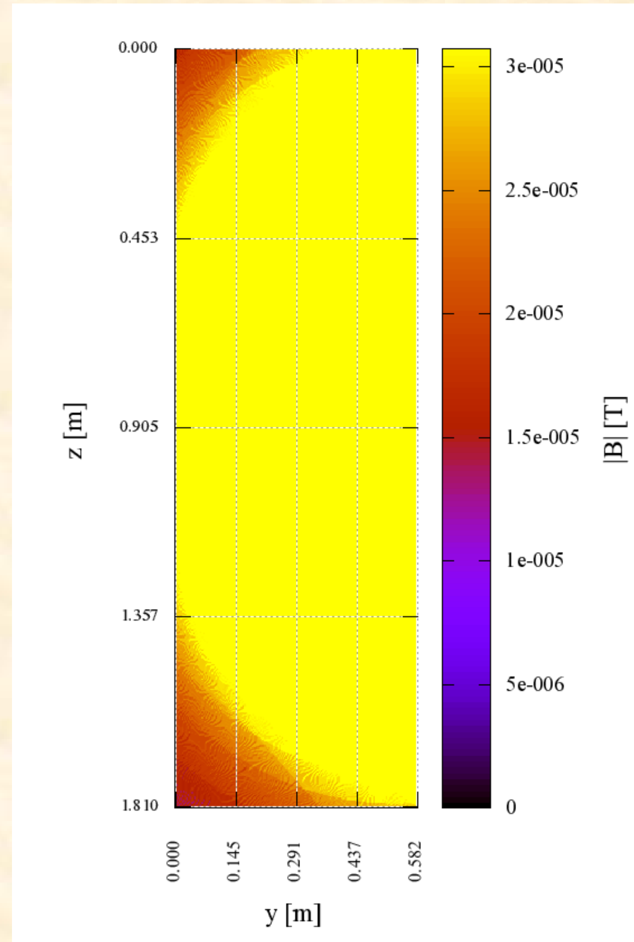
Median sagittal section
(x=0,3 m)

The maximum value (close to the hands ant to the coils) is over 2,5 mT

The major part of the body volume is over the action value 30,7 μT



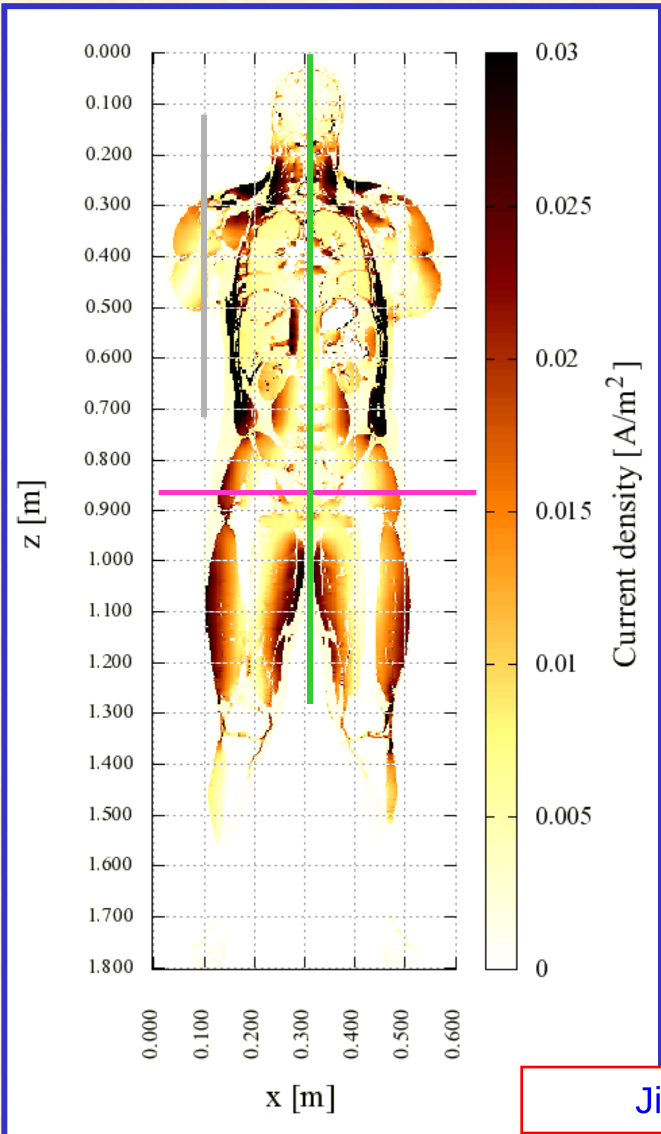




distribution of J (peak)

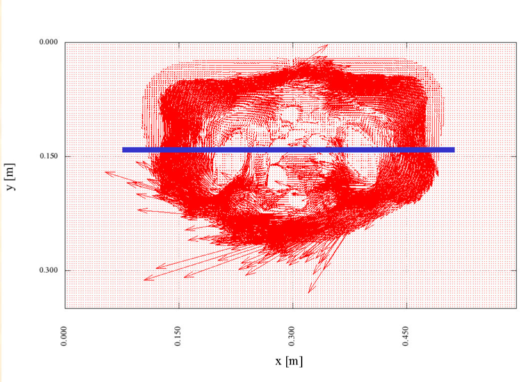
Coronal section

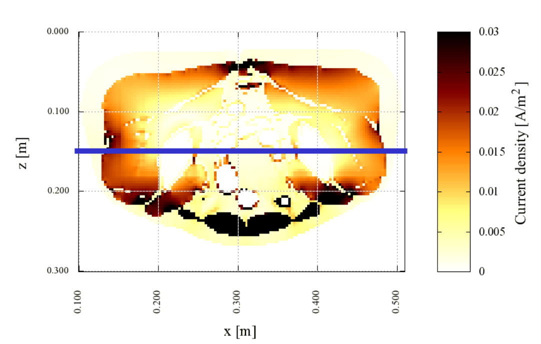
(y=0,15 m)

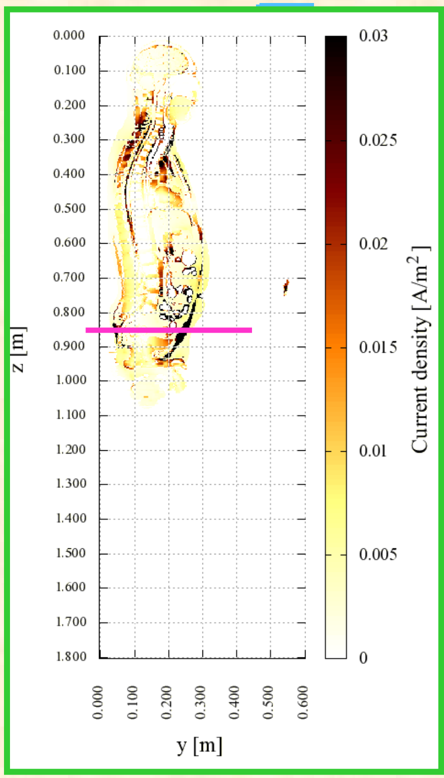


Axial section

(z=0,85 m)

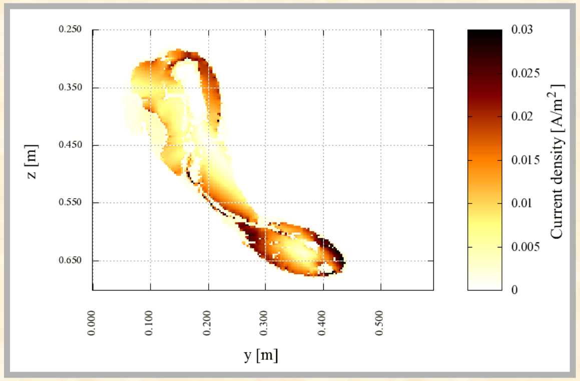






Sagittal section

(x=0,30 m)



Sagittal section

(x=0,10 m)

Jicnirp @ 3450 Hz = 0,0345 A/m^2

J (peak)

	$\|J\|$ local peak [mA/m^2]
Brain gray matter	7.59
Brain white matter	4.19
Cerebellum	11.00
Cerebro spinal fluid	112.79
Nerve & spinal chord	19.29
Fat	91.82
Heart	17.89
Muscle	235.13
Tendon	280.11

Exposure limit value @ 3450 Hz : **34,5** mA/m^2

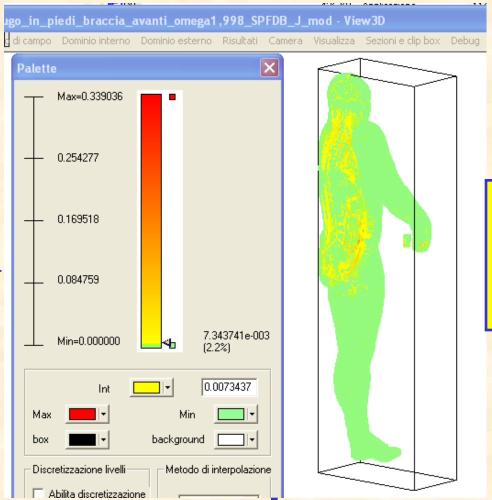
Layout of the numerical analysis

Field distribution in the body model volume

σ

SPFD

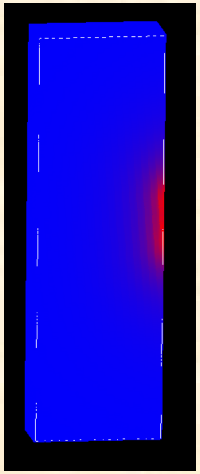
$$\Phi_{n0} = \left(\frac{1}{\sum_{i=1}^{6}\bar{\sigma}_{mi}}\right)\cdot\sum_{i=1}^{6}\left\{\bar{\sigma}_{mi}\left[\Phi_{ni} - (-1)^{i} j\omega l_c A_{mi}\right]\right\}$$

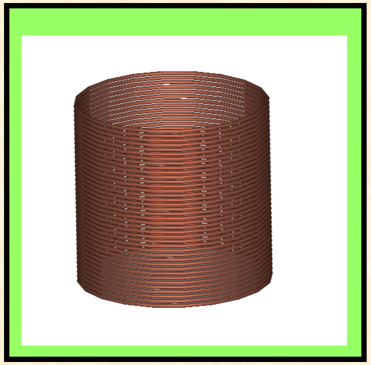


$\left|\vec{J}_{peak}\right|$

$\vec{A}$

Coil model





Surface averaging
Limitation to CNS

The compliance analysis ends with the comparison of the current density surface average ($1cm^2$) limited to CNS with the exposure limit value at the source frequency

Post-processing

Once the local peak current density distribution has been calculated two other steps has to be done :

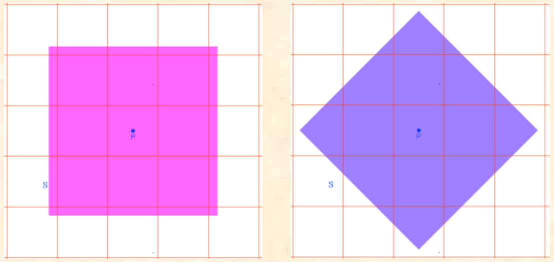
- **Surface average** of the current density "[...] *over a cross-section of 1 cm^2 perpendicular to the current direction*" (Note 3 of Table 1 of the 2004/40 Directive)
- **Limitation to central nervous system** tissues since "*The exposure limit values on the current density are intended to protect against acute exposure effects on central nervous system tissues in the head and trunk of the body*" (Note 2 of Table 1 of the 2004/40 Directive)

Surface average: simplified algorithm

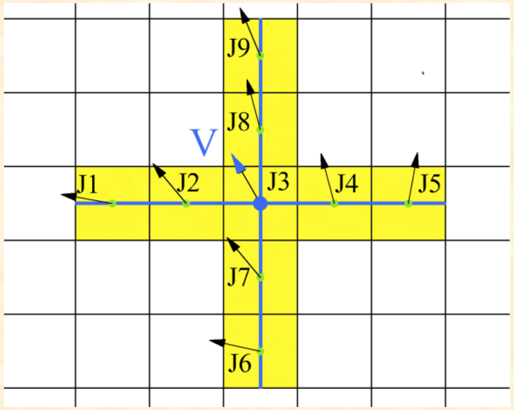
Dawson et al. [*] introduced a simplified algorithm for current density averaging. According to it: "*the components of the current density average associated with a given voxel are computed by averaging the perpendicular components of current density over squares with 1 cm edges centered on the voxel and parallel to the three principal Cartesian planes. The resulting vector field is treated similar to the current density itself in dosimetry computations*".

The simplified algorithm introduces two main approximations:

- it uses **square cross-sections** that intersect different portions of surrounding voxels, **depending on their orientations**.



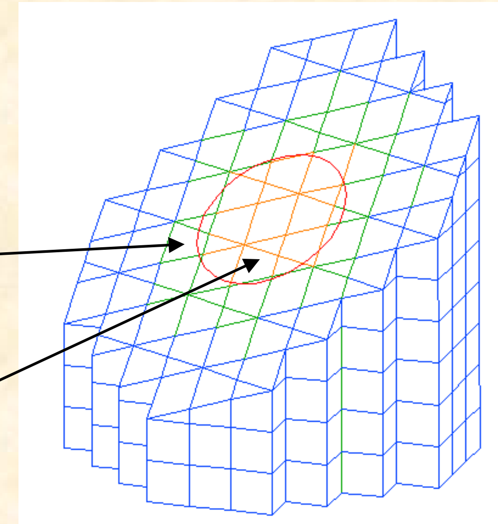
- the cross-sections used to average the current density **are not necessarily perpendicular to the current direction**, as required by the Directive.

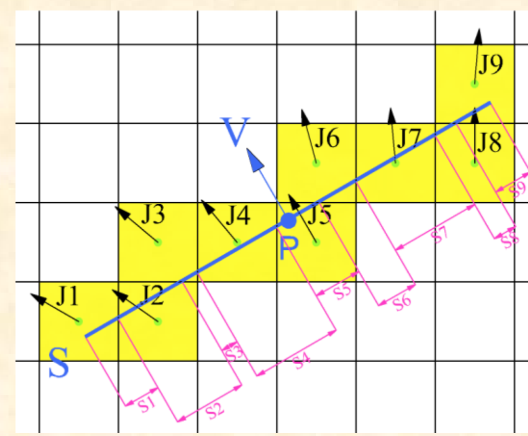


[*] T.W.Dawson, K.Caputa and M.Stuchly. *Magnetic field exposures for UK live-line workers*. Physics in Medicine and Biology, Vol.47 (2002), pp.995-1012

Surface average: “exact” algorithm

- A plane (“averaging plane”) is chosen that is perpendicular to the current density in the considered voxel (the “application point” of the average).
- The circular 1 cm^2 cross-section that lies on the averaging plane and has center in the application point is considered.
- The intersecting section *Si* of every voxel with the circular cross-section of the previous step is determined. Since, in general, the averaging plane is not necessarily perpendicular to a voxel face, this intersecting section can assume the form of a generic polygon with 3,4,5 or 6 edges.
- The cross-section average of the current density is calculated in every voxel according to the following expression:





$$J_S = \frac{\sum_{i=1}^{N} S_i \left(\vec{J}_i \cdot \vec{V}\right)}{\sum_{i=1}^{N} S_i}$$

“exact” algorithm vs simpl. algorithm

	$\lvert J\rvert$ avg 1cm² (exact) [mA/m²]	$\lvert J\rvert$ avg 1cm² (simpl.) [mA/m²]
Brain gray matter	12.51	7.71
Brain white matter	8.97	4.96
Cerebellum	16.11	9.58
Cerebro spinal fluid	32.84	77.89
Nerve & spinal chord	38.15	19.10
Fat	87.72	61.73
Heart	22.13	15.97
Muscle	85.30	164.57
Tendon	75.85	195.77

- Differences between the two averaging algorithm can be ***above 3 dB*** (with both signs)

Compliance in the Central Nervous System (CNS)

Also important, the “target tissues” for this averaging are the tissues of the central nervous system (CNS), as Note 2 of the same table specifies that “*The exposure limit values on the current density are intended to protect against acute exposure effects on central nervous system tissues in the head and trunk of the body*”.

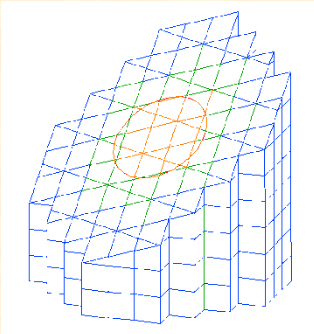
There is a problem:

When the application point of the averaging cross-section is close to a surface separating an organ of the CNS from a different tissue, the averaging cross-section will possibly intersect voxels that do not belong to the CNS.

How to proceed in such cases?

Compliance in the Central Nervous System (CNS) full averaging

In this work, **the averaging application point is always taken in a voxel that belongs to the central nervous system, but the contributes of all other voxels (even not belonging to the CNS) that intersect the averaging plane are also fully considered (FULL AVERAGING).** This choice is inspired by Note 3 of Table 1 of the Directive, that introduces the current density averaging "*because of the electrical inhomogeneity of the body*". If the aim of the averaging is to take into account the electrical inhomogeneity, it seems a nonsense to exclude some voxels once the averaging cross-section has been defined.



Results with full averaging

Exposure limit value @ 3450 Hz : **34,5** mA/m^2

	|J| *local peak* [mA/m^2]	|J| *avg 1cm^2* (exact) [mA/m^2]	|J| *avg 1cm^2* (simpl.) [mA/m^2]
Brain gray matter	7.59	12.51	7.71
Brain white matter	4.19	8.97	4.96
Cerebellum	11.00	16.11	9.58
Cerebro spinal fluid	112.79	32.84	77.89
Nerve & spinal chord	19.29	38.15	19.10

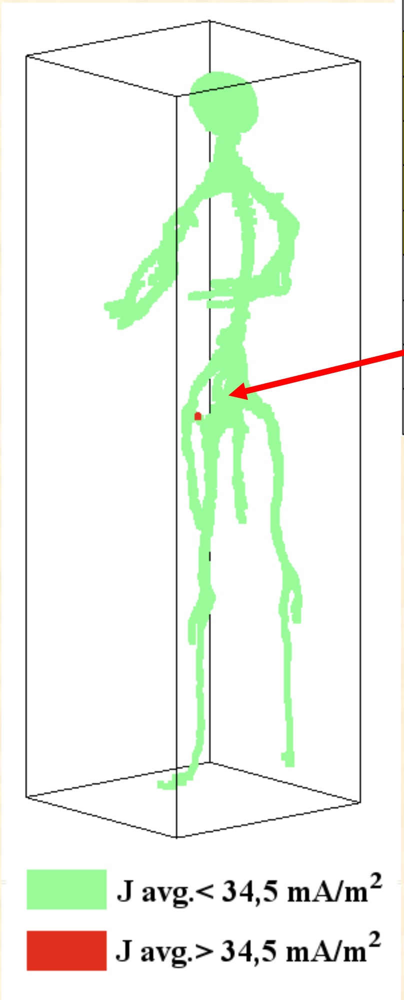
Using the full averaging algorithm the maximum surface average in some tissues is higher than the local peak. This can happen when the considered tissue is surrounded by more conductive districts.

Alternative aproaches to the limitation to CNS

$$J_S = \frac{\sum_{i=1}^{N} S_i \left(\vec{J}_i \cdot \vec{V}\right)}{\sum_{i=1}^{N} S_i}$$

- **ZERO WEIGHTING**: the averaging application point is always taken in a voxel that belongs to the central nervous system, and the contributes of all the voxels not belonging to the CNS that intersect the averaging plane are zero weighted on numerator (the averaging surface is effectively 1 cm^2).
- **PARTIAL AVERAGE**: the averaging application point is always taken in a voxel that belongs to the central nervous system, and the contributes of all the voxels not belonging to the CNS that intersect the averaging plane are not considered at all (zero weighted on both numerator and denominator; the averaging surface could be less than 1 cm^2).

Results: is the presented case compliant with EU Directive?



	$\lvert J \rvert$ avg 1cm² (exact) [mA/m²]	$\lvert J \rvert$ avg 1cm² (simpl.) [mA/m²]
Brain gray matter	12.51	7.71
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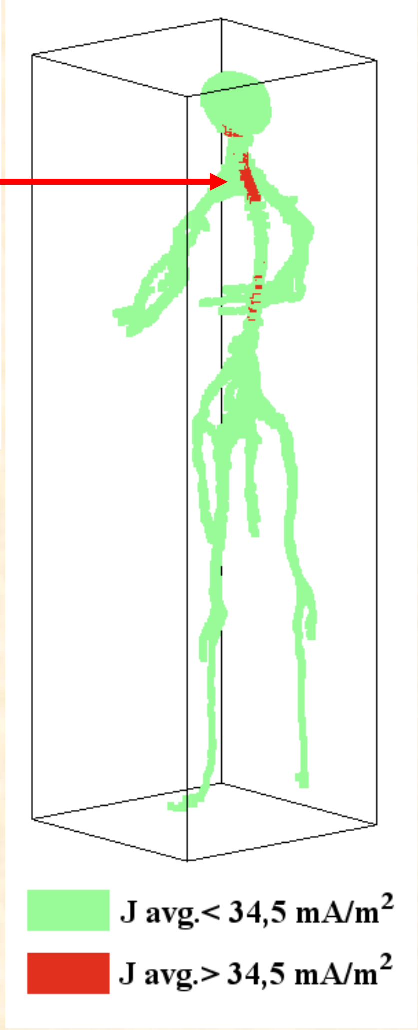

- Using the geometrical algorithm the exposure limit value is exceeded in the peripheral nerves of the pelvis region.
- Using the simplified algorithm the exposure limit value is exceeded in the cerebro-spinal fluid.

Final remarks

While the calculus of the local peak distribution of the current density is straightforward, in the post processing steps there are some key questions that are not completely specified both in directive and in the literature:

- **Limitation to the Central Nervous System**:
  - Whatever is the group of tissues considered part of CNS, different algorithms are possible to do the surface average of current density close to the interfaces between CNS and not-CNS tissues.
- **Surface averaging method**:
  - Adopting two different algorithms leads in this case to differences of more than 3 dB
  - The concept of cross-section perpendicular to a vector with elliptic or circular polarization is not well defined and the choice of the cross-section orientation is arbitrary