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Numerical assessment of induced current density due to occupational exposure to MR gradient fields

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Introduction and Summary

Set Up for Gradient Field Measurement in MRI
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ORAL SESSIONS Instrumentation & Methodology
Sala del Chiostro

patients.
The assessment process involves two distinct phases:
(1)measurement of the fields generated by the MR scanner and
(2)numerical calculation of the dosimetric quantities induced by the fields in a human body represented with a proper digital model.

i. Movement in a static field distribution.
ii. Exposure to the magnetic field generated by gradient coils
iii. Exposure to RF fields

In this presentation:
- basics of the dosimetric method (in time domain) used to calculate the physical quantities (and the related exposure indexes) induced in a worker exposed to magnetic fields generated by MRI gradient coils
- some examples of application, focusing on the comparison of ICNIRP 1998 – ICNIRP 2010 exposure standards

Desired characteristics of the dosimetric method

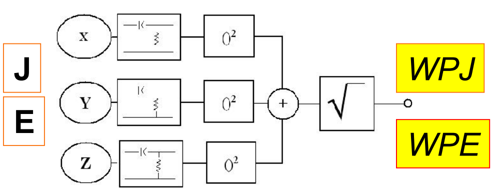
Focusing the attention on the time evolution of the exposures and not to the space distribution of the field.

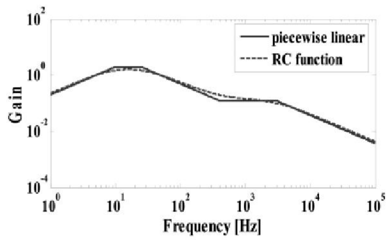
Suitable to treat exposures to complex waveform (not sinusoidal) impressed fields with general polarization.

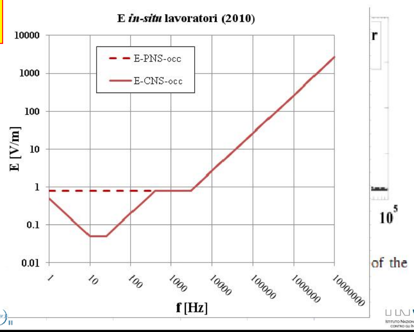
Avoids the spectral decomposition of the problem (not convenient in case of several spectral components and in relation to the so called “spectral leakage” phenomenon).

Allows the assessment of the compliance with ICNIRP basic restrictions that vary with frequency

Weighted peak approach

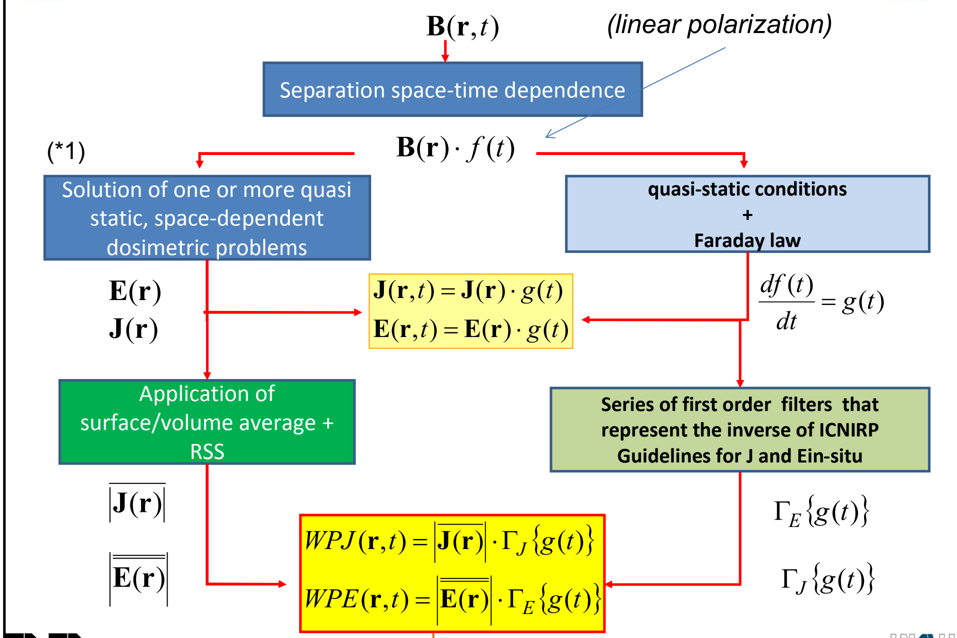






$$\left|\sum_i \frac{A_i}{EL_i}\cos(2\pi f_i t + \theta_i + \varphi_i)\right| \leq 1,$$

Weighted peak dosimetry at low frequencies



B spatial distribution

- If both the **shapes** of the three **gradient coils** and the **currents** flowing into them were known, the general problem could be separated into three linearly polarized field problems (one per coil).

$$\mathbf{B}(\mathbf{r},t) \equiv \mathbf{B}_{Xcoil}(\mathbf{r},t) + \mathbf{B}_{Ycoil}(\mathbf{r},t) + \mathbf{B}_{Zcoil}(\mathbf{r},t)$$

where

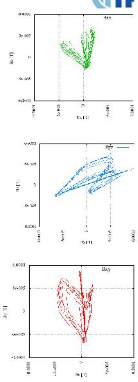
$$\begin{cases} \mathbf{B}_{Xcoil}(\mathbf{r},t) = f_{Xcoil}(t)\cdot \mathbf{B}_{Xcoil}(\mathbf{r}) \\ \mathbf{B}_{Ycoil}(\mathbf{r},t) = f_{Ycoil}(t)\cdot \mathbf{B}_{Ycoil}(\mathbf{r}) \\ \mathbf{B}_{Zcoil}(\mathbf{r},t) = f_{Zcoil}(t)\cdot \mathbf{B}_{Zcoil}(\mathbf{r}) \end{cases}$$

"time-shape" of coil current

- Since it is not easy to obtain such data from MRI manufacturers, **the spatial distribution was simplified by adopting a homogeneous worst-case approach**. In particular, the magnetic flux density vs. time was measured in a selected point for each exposure scenario; this is the point closest to the bore where a worker may have to stay during a scan.

Homogeneous B field, general polarization

Not parallel to x



$$\mathbf{B}(\mathbf{r},t) \equiv \mathbf{B}(t) = \hat{x}B_x(t) + \hat{y}B_y(t) + \hat{z}B_z(t)$$

$$\mathbf{J}(\mathbf{r},t) = \overbrace{\frac{dB_x(t)}{dt}}^{g_1(t)}\mathbf{j}_1(\mathbf{r}) + \overbrace{\frac{dB_y(t)}{dt}}^{g_2(t)}\mathbf{j}_2(\mathbf{r}) + \overbrace{\frac{dB_z(t)}{dt}}^{g_3(t)}\mathbf{j}_3(\mathbf{r})$$

$$WPJ_X(\mathbf{r},t) = \bar{j}_{1x}(\mathbf{r})\Gamma_J\{g_1(t)\} + \bar{j}_{2x}(\mathbf{r})\Gamma_J\{g_2(t)\} + \bar{j}_{3x}(\mathbf{r})\Gamma_J\{g_3(t)\}$$

$$WPJ_Y(\mathbf{r},t) = \bar{j}_{1y}(\mathbf{r})\Gamma_J\{g_1(t)\} + \bar{j}_{2y}(\mathbf{r})\Gamma_J\{g_2(t)\} + \bar{j}_{3y}(\mathbf{r})\Gamma_J\{g_3(t)\}$$

$$WPJ_Z(\mathbf{r},t) = \bar{j}_{1z}(\mathbf{r})\Gamma_J\{g_1(t)\} + \bar{j}_{2z}(\mathbf{r})\Gamma_J\{g_2(t)\} + \bar{j}_{3z}(\mathbf{r})\Gamma_J\{g_3(t)\}$$

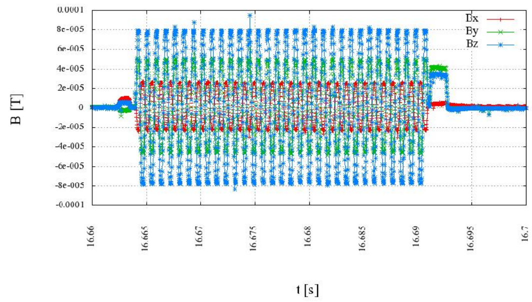
$$WPJ(\mathbf{r},t) = \sqrt{[WPJ_X(\mathbf{r},t)]^2 + [WPJ_Y(\mathbf{r},t)]^2 + [WPJ_Z(\mathbf{r},t)]^2}$$

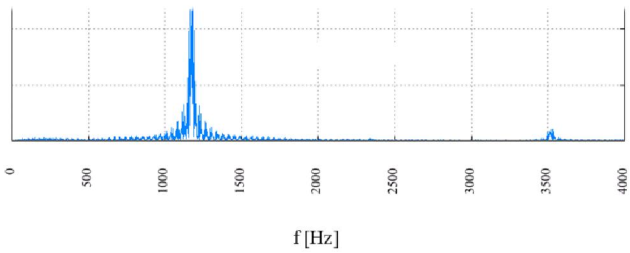
(*2)

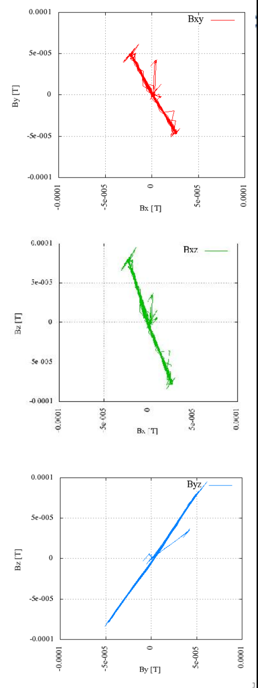
Measured gradient sequencies

sequence	|B| [T]	WP03 occupational	WP03 population	WP10 occupational	WP10 population
2009-07-25_x1	1.14E-04	**2.436**	12.013	**0.415**	1.570
2009-07-25_x2	1.10E-04	**2.407**	11.871	**0.409**	1.549
2009-07-25_x3	6.53E-05	**1.125**	5.555	**0.210**	0.786
2009-07-25_x4	1.02E-04	**1.260**	6.231	**0.234**	0.902
2009-11-06_x8y8z8	3.31E-06	**0.039**	0.194	**0.006**	0.025
2009-11-06_x9y9z9	1.10E-06	**0.017**	0.085	**0.003**	0.013
2010-01-29_x1y1z1	6.40E-05	**0.906**	4.499	**0.143**	0.570
2010-01-29_x2y2z2	1.10E-04	**1.575**	7.849	**0.212**	0.860
2010-01-29_x3y3z3	1.18E-04	**1.555**	7.720	**0.235**	0.915
2010-01-29_x4y4z4	1.13E-04	**1.454**	7.263	**0.191**	0.789

B(t) 2009_07_25_x1



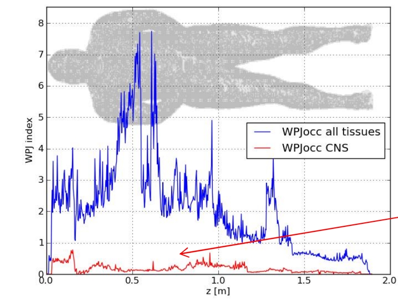




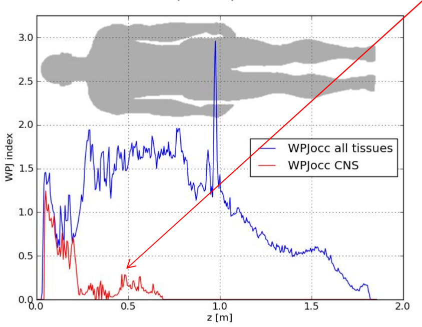
WPJ

- **Maximum** of WPJ index on every axial section in function of section position
- The assessment of ICNIRP 1998 basic restrictions regards only CNS

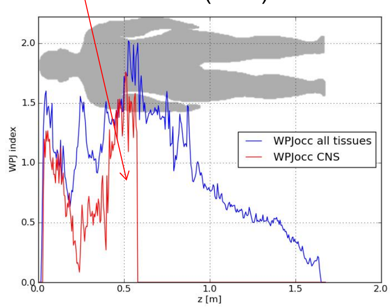
Man (VHP) 3mm



Man (IT'IS) 5mm



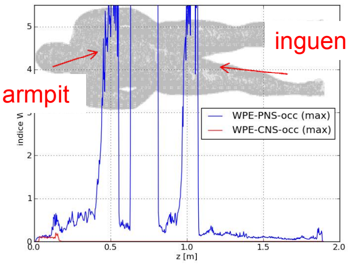
Woman (IT'IS) 5mm



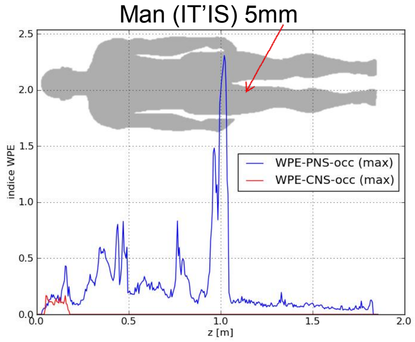
WPE

High WPE indexes in dry skin are present also in IT'IS body models but are less evident, especially in 99 percentiles (graphs refer to maximum values). This can be due to lower resolution and different anatomy (better refinement, for example arm-trunk contact in VHP).

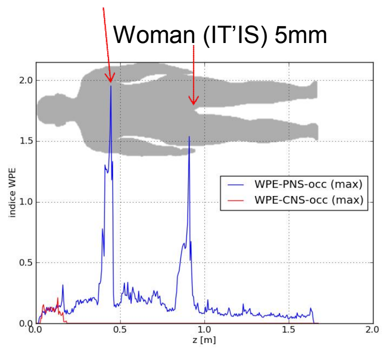
Man (VHP) 3mm



Man (IT'IS) 5mm

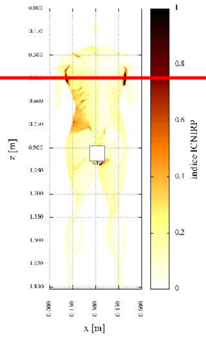


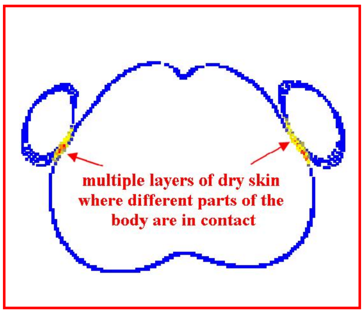
Woman (IT'IS) 5mm



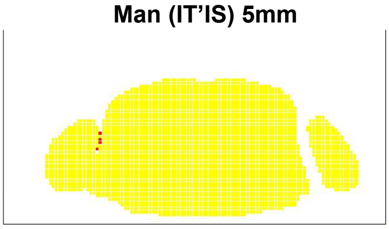
WPE index in dry skin

Man (VHP) 3mm

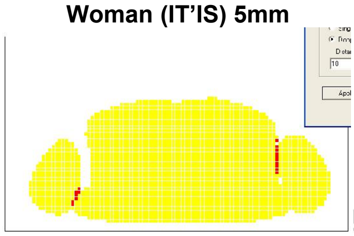




Man (IT'IS) 5mm



Woman (IT'IS) 5mm

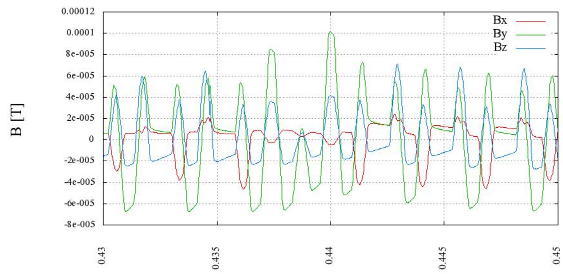


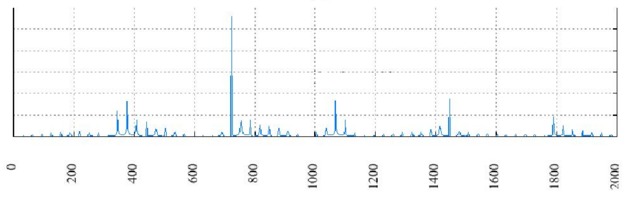
sequence	|B| [T]	WP03 occupational	WP10 occupational
2009-07-25_x1	1.14E-04	244 %	42 %

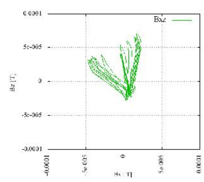
	WPJ CNS occupational	WPE CNS head occupational	WPE PNS occupational
Man (VHP) 3mm	77%	10%	532% (31%)
Man (IT'IS) 5mm	124%	10%	34% (29%)
Woman (IT'IS) 5mm	176%	9%	28% (18%)

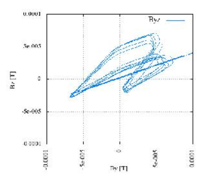
99 %ile

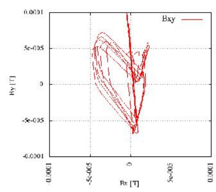
B(t) 2010_01_29_x2y2z2











sequence	|B| [T]	WP03 occupational	WP10 occupational
2010-01-29_x2y2z2	1.10E-04	158 %	21 %

	WPJ CNS occupational	WPE CNS head occupational	WPE PNS occupational
Man (VHP) 3mm	28%	4%	218% (13%)
Man (IT'IS) 5mm	67%	5%	15% (12%)
Woman (IT'IS) 5mm	84%	5%	11% (9%)

Conclusions

- A method has been presented that applies the WP approach to the calculation of basic dosimetric quantities, that aims at the calculation of two exposure indexes called WPJ (ICNIRP1998) and WPE (ICNIRP2010).
- The presented method has been applied to the case of the magnetic field generated by MRI gradient coils. That kind of exposure can, in some case, be critical in terms of BR compliance.
- A possible problem in terms of respect of 2010 Guidelines rationale has been evidenced, that refers to low conductivity peripheral tissues (dry skin). This problem has to be investigated moving towards higher resolution body models.
- The comparison shows that with the new Guidelines is necessary to put great attention in the choice of the digital body models that need to be accurate and refined since the new ICNIRP basic restrictions apply to all tissues.

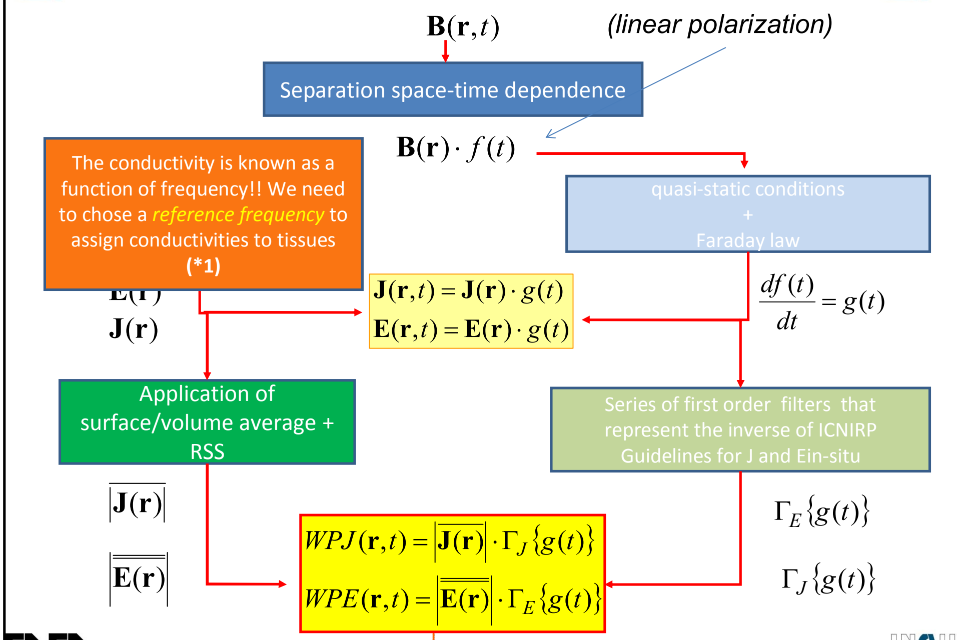
Grazie per l'attenzione

Thank you for your attention

Non-Homogeneous B field, general polarization

- If both the shape of the three gradient coils and the currents flowing into them were known, the general problem could be divided into three linearly polarized field problems (one per coil)
- An extension of the presented method was developed that allows to calculate the WPJ and WPE indexes starting from B field measurements, moving the same instrument in a set of fixed points disposed in convenient way. This extension entails:
  - the interpolation of the spatial field (and the vector potential) distribution from measured values;
  - some approximations to synchronize the measured B field frames in time.

Weighted peak dosimetry at low frequencies



(*1) the choice of the reference frequency

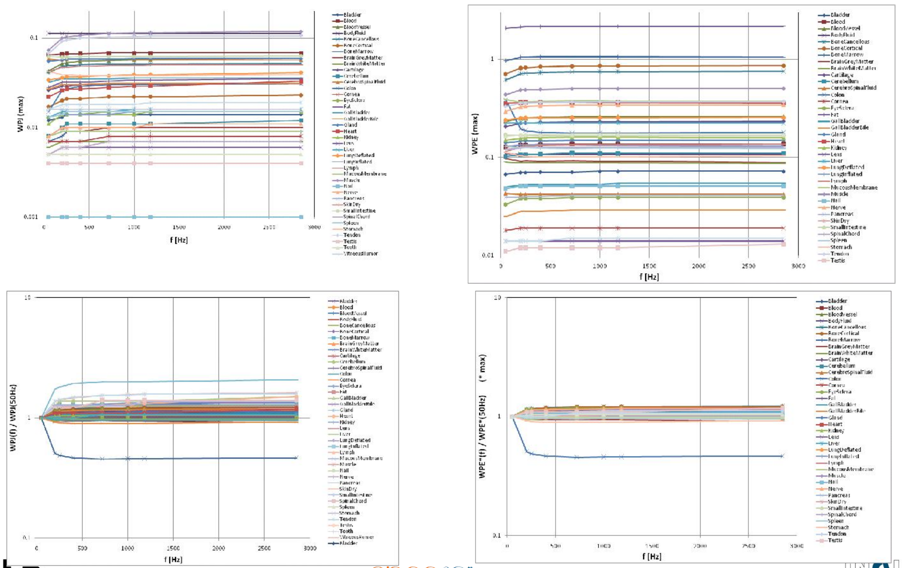
- the instant t* is considered when the RSS of the three indexes $\Gamma_{J\ or\ E}\{g_i(t)\}$ reaches its maximum

$$\sqrt{\Gamma_{J\,or\,E}\{g_1(t)\}^2 + \Gamma_{J\,or\,E}\{g_2(t)\}^2 + \Gamma_{J\,or\,E}\{g_3(t)\}^2}$$

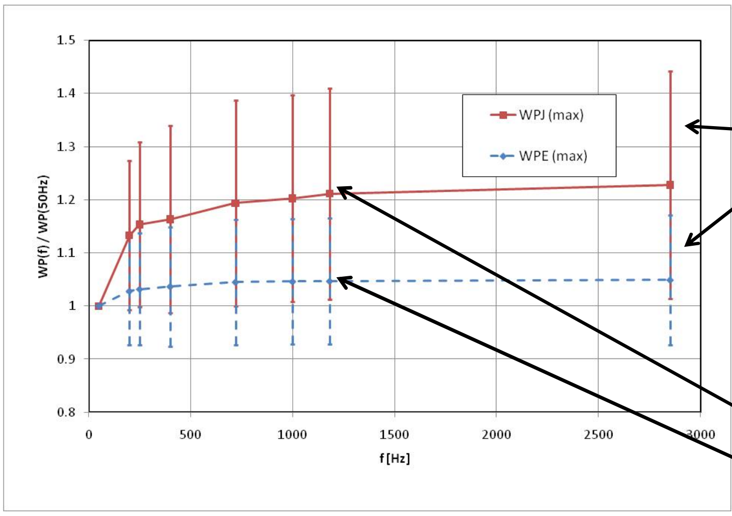
- The DFT of the three indexes $\Gamma_{J\ or\ E}\{g_i(t)\}$ is calculated on a time frame centered in t* with a time length suitable to obtain a sufficient spectral resolution (0.5s -> 2Hz in the presented cases)
- For each frequency of the spectrum the RSS of the spectral row of the three indexes $\Gamma_{J\ or\ E}\{g_i(t)\}$ is calculated.
- The frequency for which the maximum of the previously cited quantity holds is adopted as reference frequency.

(*1) the choice of the reference frequency

WPJ | WPE



(*1) the choice of the reference frequency

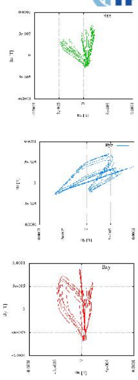


Standard deviation of the WP index calculated on different tissues at the fixed frequency on x axis

Mean of the WP index calculated on different tissues at the fixed frequency on x axis

Homogeneous B field, general polarization

Not parallel to x



$$\mathbf{B}(\mathbf{r},t) \equiv \mathbf{B}(t) = \hat{x}B_x(t) + \hat{y}B_y(t) + \hat{z}B_z(t)$$

$g_1(t)$ $g_2(t)$ $g_3(t)$

$$\mathbf{J}(\mathbf{r},t) = \frac{dB_x(t)}{dt}\mathbf{j_1}(\mathbf{r}) + \frac{dB_y(t)}{dt}\mathbf{j_2}(\mathbf{r}) + \frac{dB_z(t)}{dt}\mathbf{j_3}(\mathbf{r})$$

$$WPJ_X(\mathbf{r},t) = \bar{j}_{1x}(\mathbf{r})\Gamma_J\{g_1(t)\} + \bar{j}_{2x}(\mathbf{r})\Gamma_J\{g_2(t)\} + \bar{j}_{3x}(\mathbf{r})\Gamma_J\{g_3(t)\}$$
$$WPJ_Y(\mathbf{r},t) = \bar{j}_{1y}(\mathbf{r})\Gamma_J\{g_1(t)\} + \bar{j}_{2y}(\mathbf{r})\Gamma_J\{g_2(t)\} + \bar{j}_{3y}(\mathbf{r})\Gamma_J\{g_3(t)\}$$
$$WPJ_Z(\mathbf{r},t) = \bar{j}_{1z}(\mathbf{r})\Gamma_J\{g_1(t)\} + \bar{j}_{2z}(\mathbf{r})\Gamma_J\{g_2(t)\} + \bar{j}_{3z}(\mathbf{r})\Gamma_J\{g_3(t)\}$$

Some difficoulties arise to find the time instant when this quantity reaches its maximum (*2)

(*2) Finding the time-maximum of WP indexes

Non-homogeneous B field with linear polarization

$$\max_t\{WPJ(\mathbf{r},t)\} = \left|\overline{\mathbf{J}(\mathbf{r})}\right| \cdot \max_t\{\Gamma_J\{g(t)\}\}$$
$$\max_t\{WPE(\mathbf{r},t)\} = \left|\overline{\mathbf{E}(\mathbf{r})}\right| \cdot \max_t\{\Gamma_E\{g(t)\}\}$$

Homogeneous B field with generic polarization

$$\max_t\{WPJ_X(\mathbf{r},t)\} \neq \bar{j}_{1x}(\mathbf{r})\max_t\{\Gamma_J\{g_1(t)\}\} + \bar{j}_{2x}(\mathbf{r})\max_t\{\Gamma_J\{g_2(t)\}\} + \bar{j}_{3x}(\mathbf{r})\max_t\{\Gamma_J\{g_3(t)\}\}$$
$$\max_t\{WPJ_Y(\mathbf{r},t)\} \neq \bar{j}_{1y}(\mathbf{r})\max_t\{\Gamma_J\{g_1(t)\}\} + \bar{j}_{2y}(\mathbf{r})\max_t\{\Gamma_J\{g_2(t)\}\} + \bar{j}_{3y}(\mathbf{r})\max_t\{\Gamma_J\{g_3(t)\}\}$$
$$\max_t\{WPJ_Z(\mathbf{r},t)\} \neq \bar{j}_{1z}(\mathbf{r})\max_t\{\Gamma_J\{g_1(t)\}\} + \bar{j}_{2z}(\mathbf{r})\max_t\{\Gamma_J\{g_2(t)\}\} + \bar{j}_{3z}(\mathbf{r})\max_t\{\Gamma_J\{g_3(t)\}\}$$

$$\max_t\{WPJ(\mathbf{r},t)\} = \max_t\left\{\sqrt{[WPJ_X(\mathbf{r},t)]^2 + [WPJ_Y(\mathbf{r},t)]^2 + [WPJ_Z(\mathbf{r},t)]^2}\right\} =$$

??

(*2) Finding the maximum in time of WP indexes

Homogeneous B field with generic polarization

$$\max_t\{WPJ_X(\mathbf{r},t)\} \neq \bar{j}_{1x}(\mathbf{r})\max_t\{\Gamma_J\{g_1(t)\}\} + \bar{j}_{2x}(\mathbf{r})\max_t\{\Gamma_J\{g_2(t)\}\} + \bar{j}_{3x}(\mathbf{r})\max_t\{\Gamma_J\{g_3(t)\}\}$$

$$\max_t\{WPJ_Y(\mathbf{r},t)\} \neq \bar{j}_{1y}(\mathbf{r})\max_t\{\Gamma_J\{g_1(t)\}\} + \bar{j}_{2y}(\mathbf{r})\max_t\{\Gamma_J\{g_2(t)\}\} + \bar{j}_{3y}(\mathbf{r})\max_t\{\Gamma_J\{g_3(t)\}\}$$

$$\max_t\{WPJ_Z(\mathbf{r},t)\} \neq \bar{j}_{1z}(\mathbf{r})\max_t\{\Gamma_J\{g_1(t)\}\} + \bar{j}_{2z}(\mathbf{r})\max_t\{\Gamma_J\{g_2(t)\}\} + \bar{j}_{3z}(\mathbf{r})\max_t\{\Gamma_J\{g_3(t)\}\}$$

- In a worst case perspective the time-maximum values of the quantities $\Gamma_J\{g_i(t)\}$ can be chosen, even if the three maximum are not simutaneous.
- the instant t* is considered when the maximum of the RSS of the three indexes $\Gamma_J\{g_i(t)\}$ holds

$$\sqrt{\Gamma_J\{g_1(t)\}^2 + \Gamma_J\{g_2(t)\}^2 + \Gamma_J\{g_3(t)\}^2}$$

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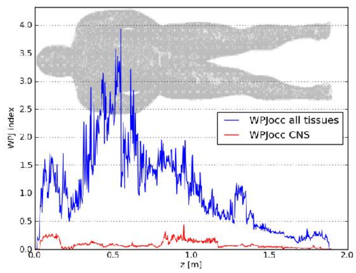
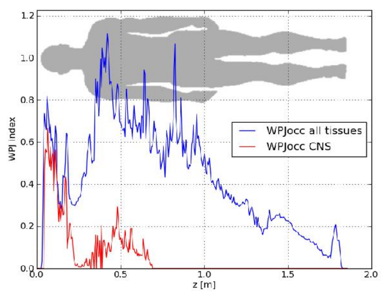
Man (VHP) 3mm

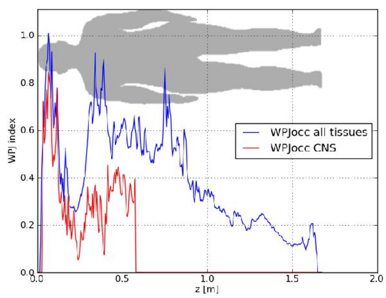


WPJ 2010_01_29_x2y2z2

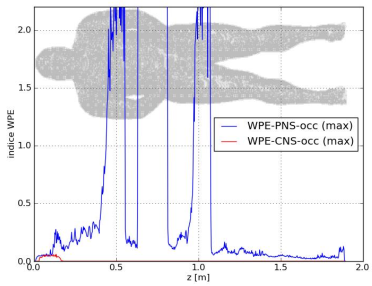
Man (ITIS) 5mm



Woman (ITIS) 5mm

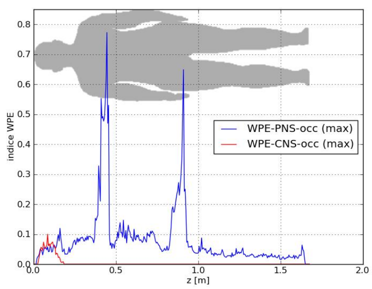


Man (VHP) 3mm

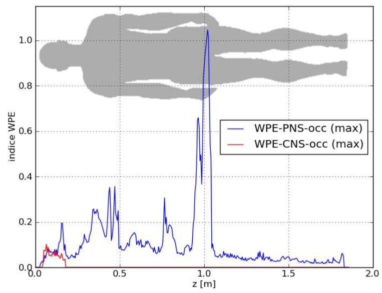


WPE
2010_01_29_x2y2z2

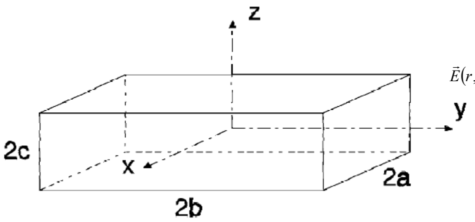
Man (ITIS) 5mm



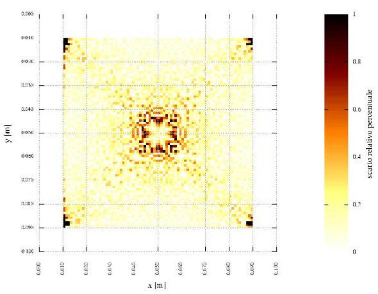
Woman (ITIS) 5mm



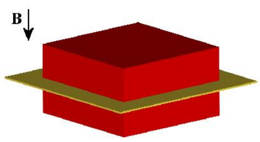
Validation



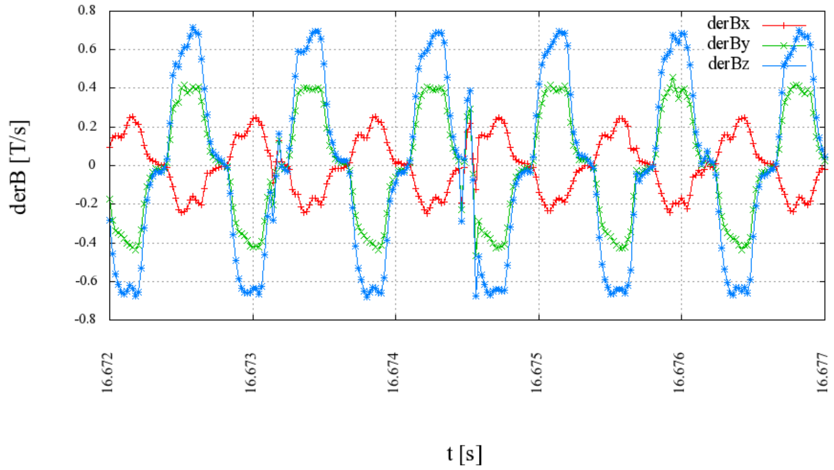
$$\vec{E}(r,\varphi,z) = j\omega\mu_0 H_0 \left(2y - 16b\sum_n \frac{1}{(n\pi)^2}\sin\left(\frac{n\pi}{2}\right)\sin\left(\frac{n\pi y}{2b}\right)\frac{\cosh\left(\frac{n\pi x}{2b}\right)}{\cosh\left(\frac{n\pi a}{2b}\right)}\right)\hat{x} + j\omega\mu_0 H_0\left(-16b\sum_n \frac{1}{(n\pi)^2}\sin\left(\frac{n\pi}{2}\right)\cos\left(\frac{n\pi y}{2b}\right)\frac{\sinh\left(\frac{n\pi x}{2b}\right)}{\cosh\left(\frac{n\pi a}{2b}\right)}\right)\hat{y}$$



$$100 \cdot \frac{\left|\vec{E}_{analytical} - \vec{E}_{numerical}\right|}{\left|\vec{E}_{analytical}\right|}$$



dB(t)/dt, E(t), J(t)



Bx=254 µT, Sinusoidal f=1182Hz

Bx254uT@1182Hz WP10=1.0					
MODEL	TESS	N	E MAX [V/m]	E 99%-ile [V/m]	WPE (BR=0.8V/m)
ugo3mm	SkinDry	167810	5.40	1.00	1.25
ella5mm	SkinDry	25398	1.03	0.28	0.35
duke5mm	SkinDry	39449	1.52	0.36	0.45