EXPOSURE LIMITS FOR STATIC MAGNETIC FIELD AND ELECTRIC FIELD INDUCED BY MOVEMENTS OF THE HUMAN BODY IN THE FIELD

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CONTENT

- Established health effects of static magnetic fields
- New ICNIRP guidelines for static magnetic fields
- Dosimetry for motion induced electric field
- Equivalent sinusoidal magnetic field
- Restriction of motion induced electric field
- Conclusions

MRI is the source of highest exposure to static magnetic fields

- Patients during MRI examination
- Medical staff (interventional radiology, radiologists)
- Staff involved with development, manufacture and maintenance

Established health effects of static magnetic fields

1) Movement induced electric field effects (> 2T)

- vertigo
- disturbance in eye-hand coordination ?
- nausea
- magnetophosphenes (visual sensations)
- metallic taste in mouth

2) Magnetic force on moving charges in blood (> 2T)

- induction of flow potentials
- EKG changes
- blood pressure changes

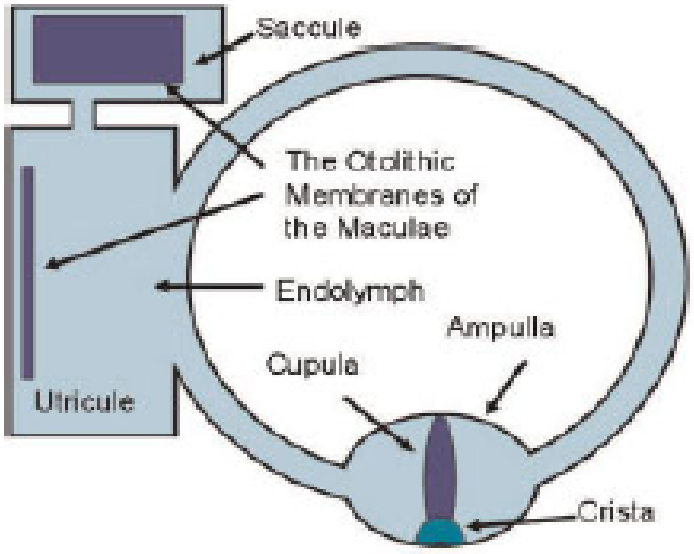
3) Acceleration of heavy or sharp metallic bodies (> 30 mT)

4) Movement of metallic body implants (>30 mT)

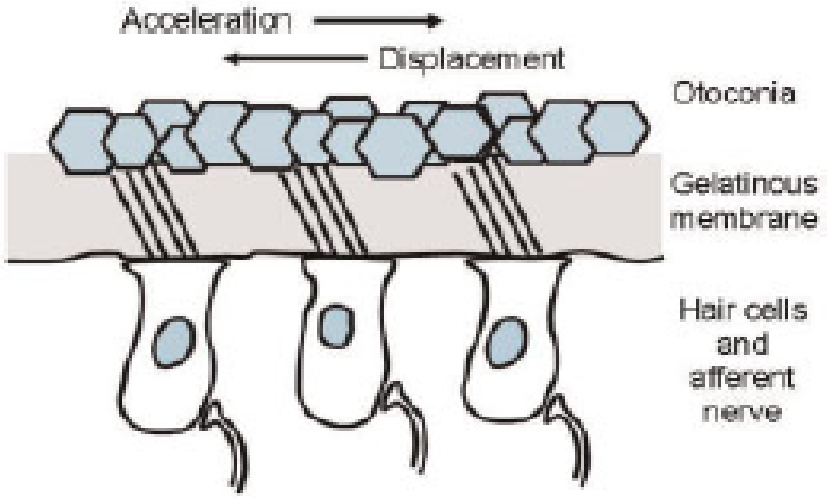
5) EM interference of cardiac pacemakers and fibrillators (>0,5 mT)

Balance sensors in the vestibular system

Otoliths and a single semicircular channel



Otolithic membrane



Glover et al. 2007

Some balance effects have been observed above 2 T also without movements

This indicates that both the static magnetic field and movement induced electric field need to be restricted

ICNIRP exposure limits for static magnetic field (2009)

Exposure characteristics	Magnetic flux density
Occupational	
Exposure of head and trunk	2 T
Exposure of limbs	8 T
General public	
Exposure of any part of the body	400 mT

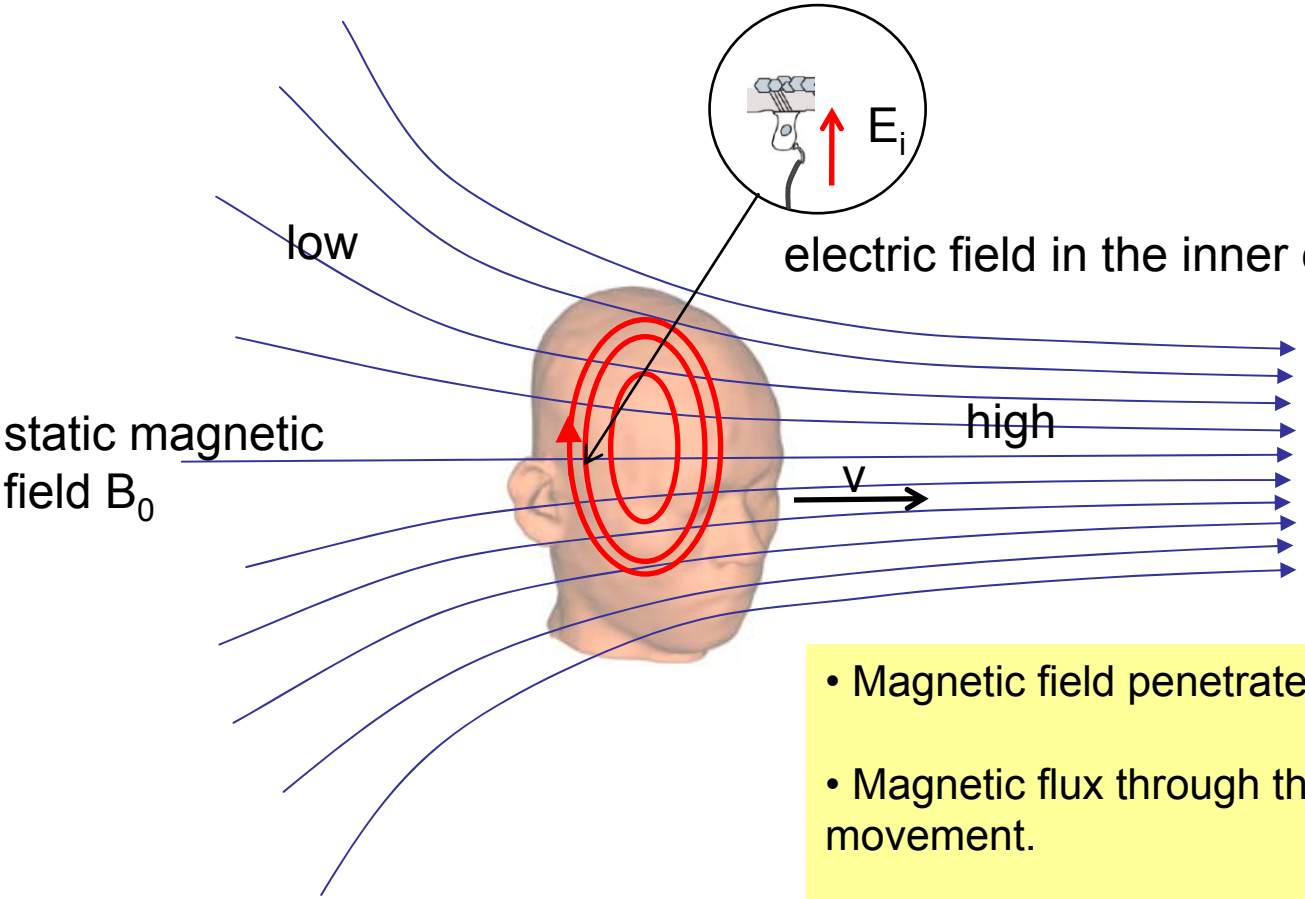
For specific work applications, exposures up to **8 T** can be justified if the environment is controlled and appropriate work practices are to control movement induced effects

ICNIRP guidelines for low-frequency EM-fields (1 Hz-100 kHz)

INTRODUCTION

..... Guidelines for static magnetic fields have been issued in a separate document (ICNIRP 2009). Guidelines applicable to movement induced electric fields or time-varying magnetic fields up to 1 Hz will be published separately.....

Electric field induced in the head moving through a magnetic field gradient



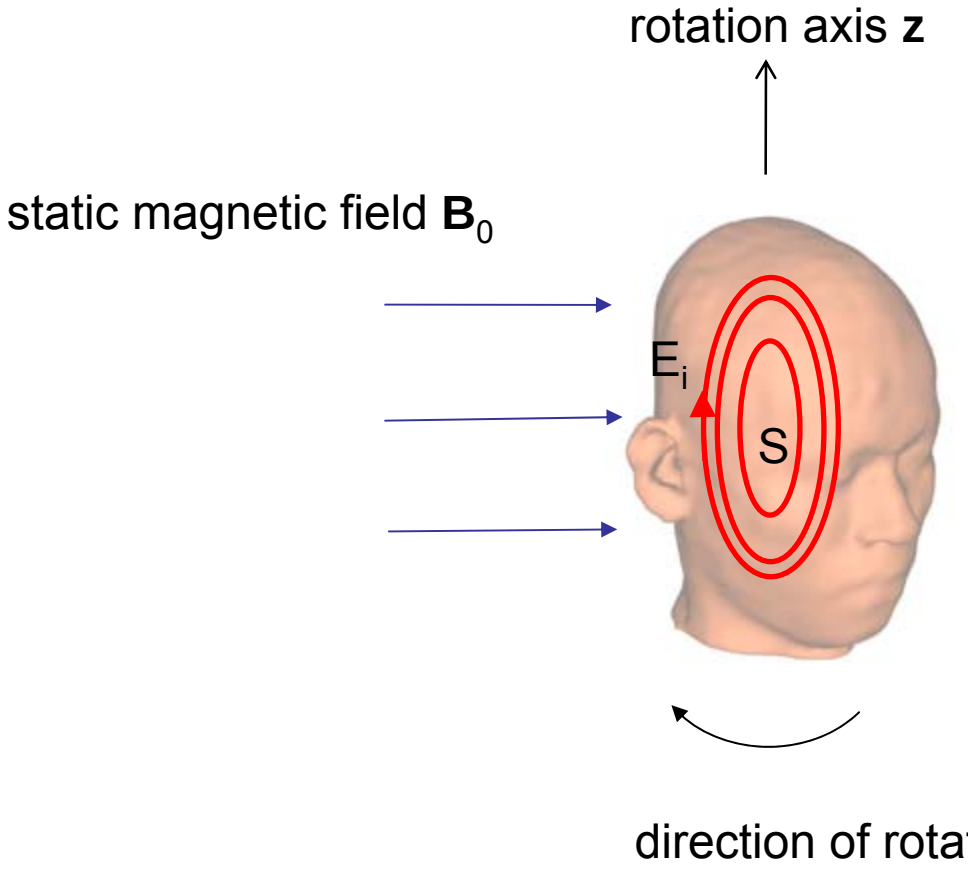
electric field in the inner ear

Faraday's law

$$\oint \mathbf{E_i} \cdot \mathbf{dl} = -\int \frac{d(\mathbf{B_0} \cdot \mathbf{dS})}{dt}$$

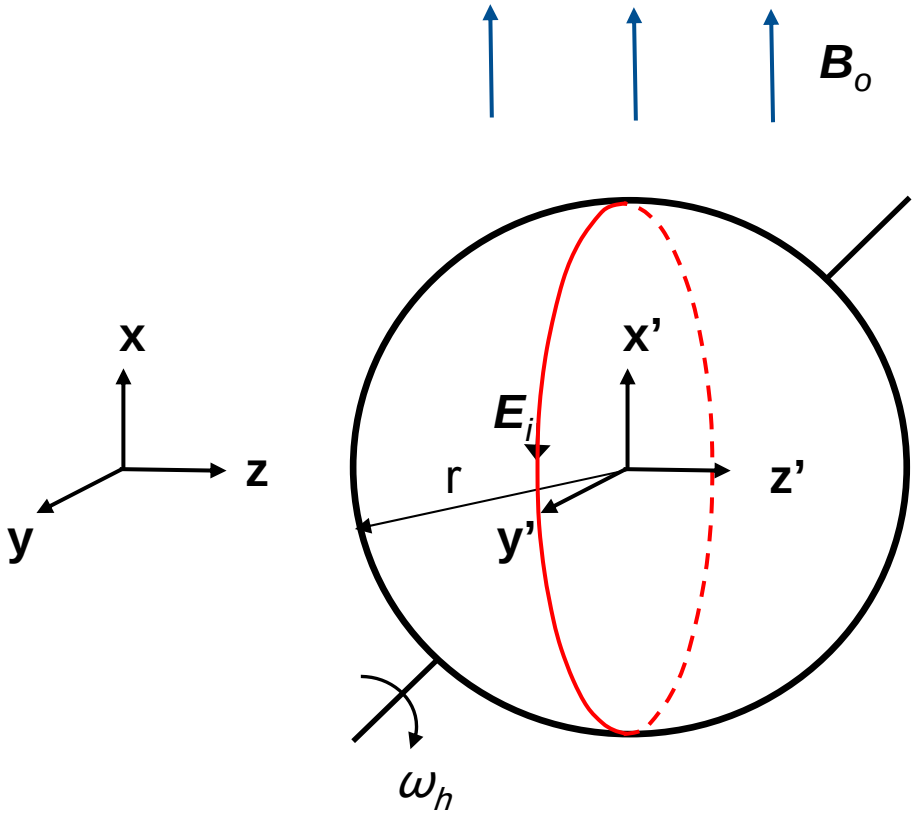
- Magnetic field penetrates the head.
- Magnetic flux through the head changes due to the movement.
- Circulating electric field is induced in the periphery of the head (Faraday's law).

Electric field induced in the head rotating in a homogeneous magnetic field



Circulating electric field is induced in cross-section S because the flux through S changes.

Electric field in a tissue equivalent sphere rotating in a static magnetic field



E_i is in maximum in the direction of $\mathbf{B}_o$.

In the coordinate frame of the sphere both fields circulate by angular velocity of the sphere ω_h.

$\omega_h B_0 \cos(\omega_h t)$ is the equivalent time-varying induced electric field

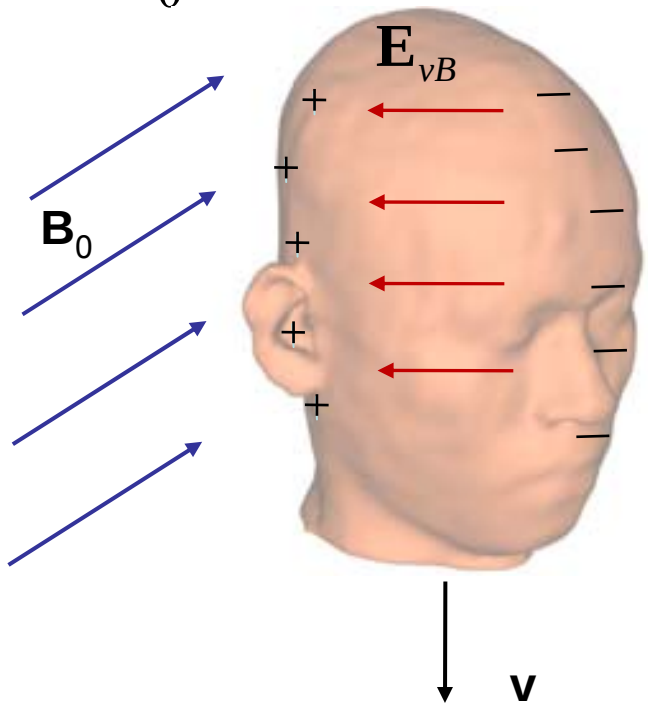
$$E_{i,max}(x',y',z') = r/2\ dB/dt = r/2\ \omega_h B_0 \cos(\omega_h t)$$

Also a transient longitudinal electric field component is induced during acceleration and deceleration.

total circulating longitudinal

$$\mathbf{E}_i = \mathbf{E}_C + \mathbf{E}_Q + \mathbf{E}_{vB}$$

$$\mathbf{E}_{vB} = \mathbf{v} \times \mathbf{B}_0$$

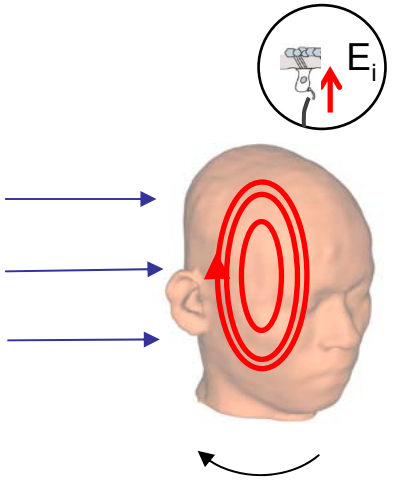


- $\mathbf{E}_{vB}$ is associated with magnetic force on moving charges.
- $\mathbf{E}_{vB}$ generates surface charges within a millisecond in a conducting human tissue.
- Only the circulating eddy current field remains significant ?

Conversion of dB/dt to induced electric field

$$E_i = CF \frac{dB}{dt}$$

CF=Conversion Factor



For a head rotating in a static magnetic field CF~0.1 V/(T/s)

Dosimetric calculations for conversion factor

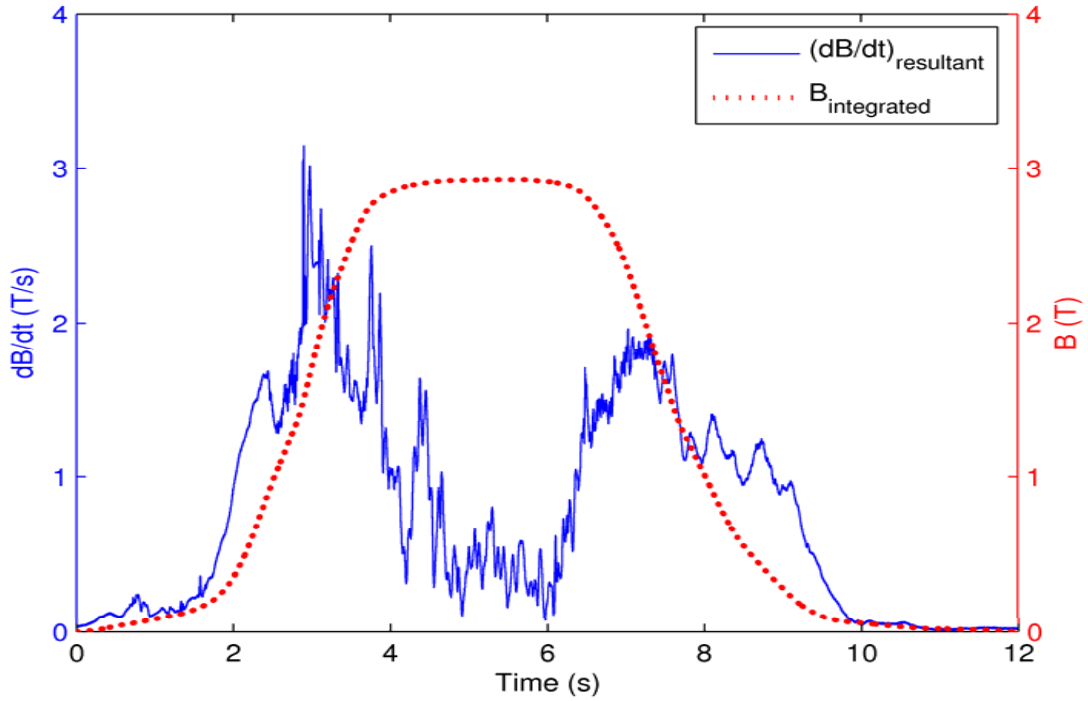
Biological body model	Conversion Factor [(mV/m)/(T/s)]	B-field, direction	Reference
Brain, NORMAN	**97.4**	homog., AP[1)]	Dimbylow 2005
Homog. sphere of 15 cm (diam.).	37.5	-	-
Retina, NORMAN	22.6	homog., AP	Dimbylow 2005
Homog. ellipsoid a=40 cm cm, b= 20 cm	140	homog., AP (perpendicular to b-axis)	IEC 60601
Heterogeneous body	340	MR-gradient, LR[2)]	Brand and Heid 2002
Heterogeneous body	200-250	MR-gradient, AP	So et al. 2004
Heterogeneous body	650[3)]	MR-gradient, AP	Bencsik et al. 2007
-	**320**	Homog.	ICNIRP 2010[4)]
Heterogeneous rotating head in static field	**95**	homog., LR	Ilvonen and Laakso 2009

1) Anterior to Posterior (front to back)
2) Left to Right
3) 3300 (mV/m)/(T/s) with clasped hands
4) From the relation of the basic restriction and reference level

Measured magnetic flux and motion induced equivalent *dB/dt* near a 3 T MRI scanner

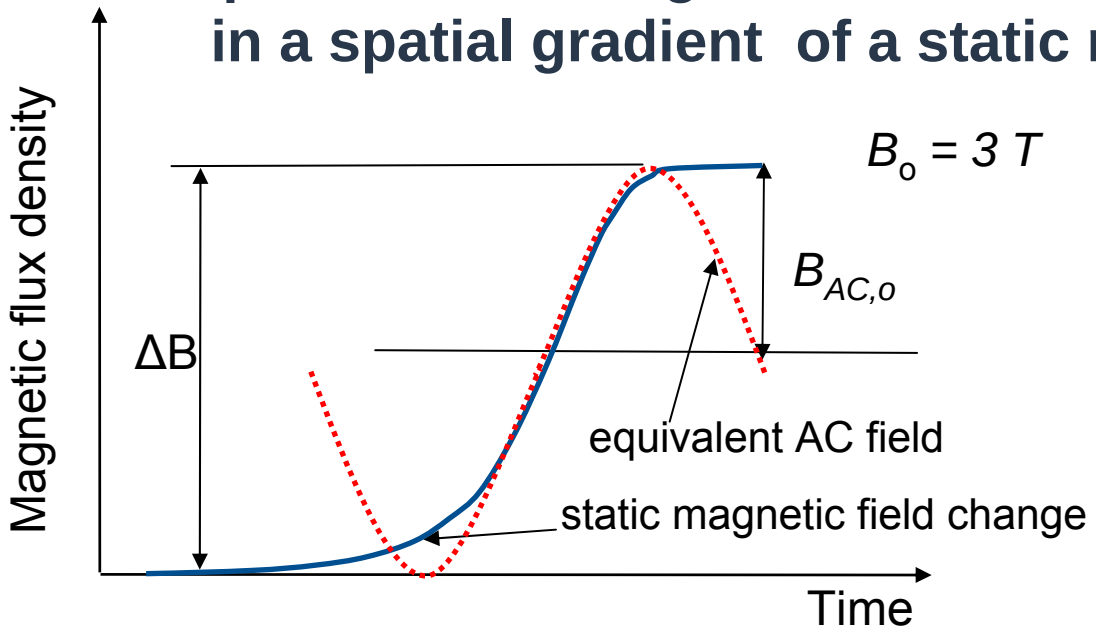
A volunteer moved with normal walking speed into and from the magnetic field of the scanner

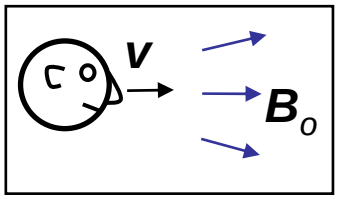
3 T scanner



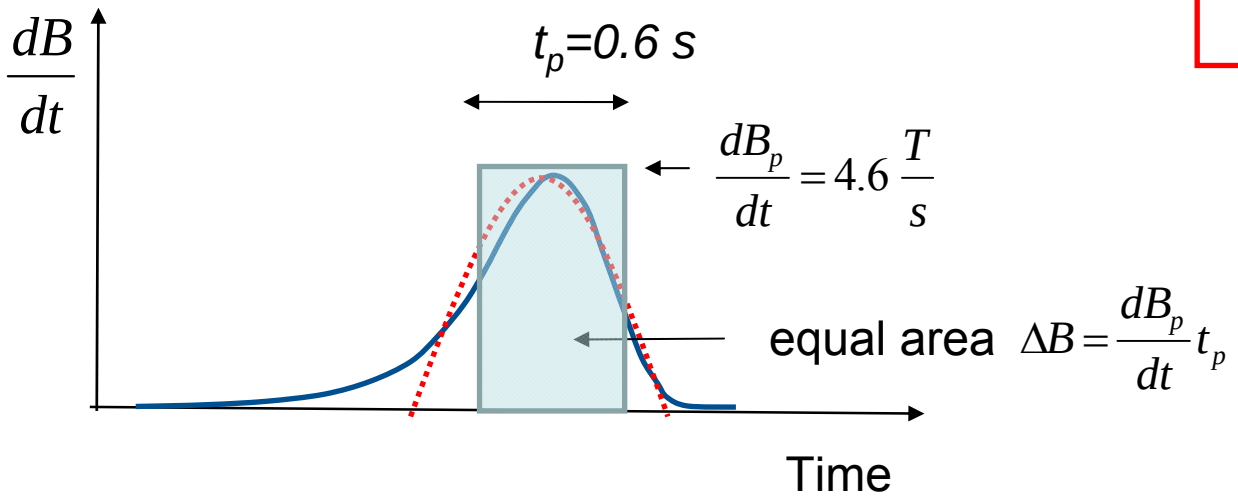
Kännälä, Toivo, Alanko, Jokela
Phys. Med. Biol. 54 (2009)

Equivalent AC magnetic field for a head moving in a spatial gradient of a static magnetic field

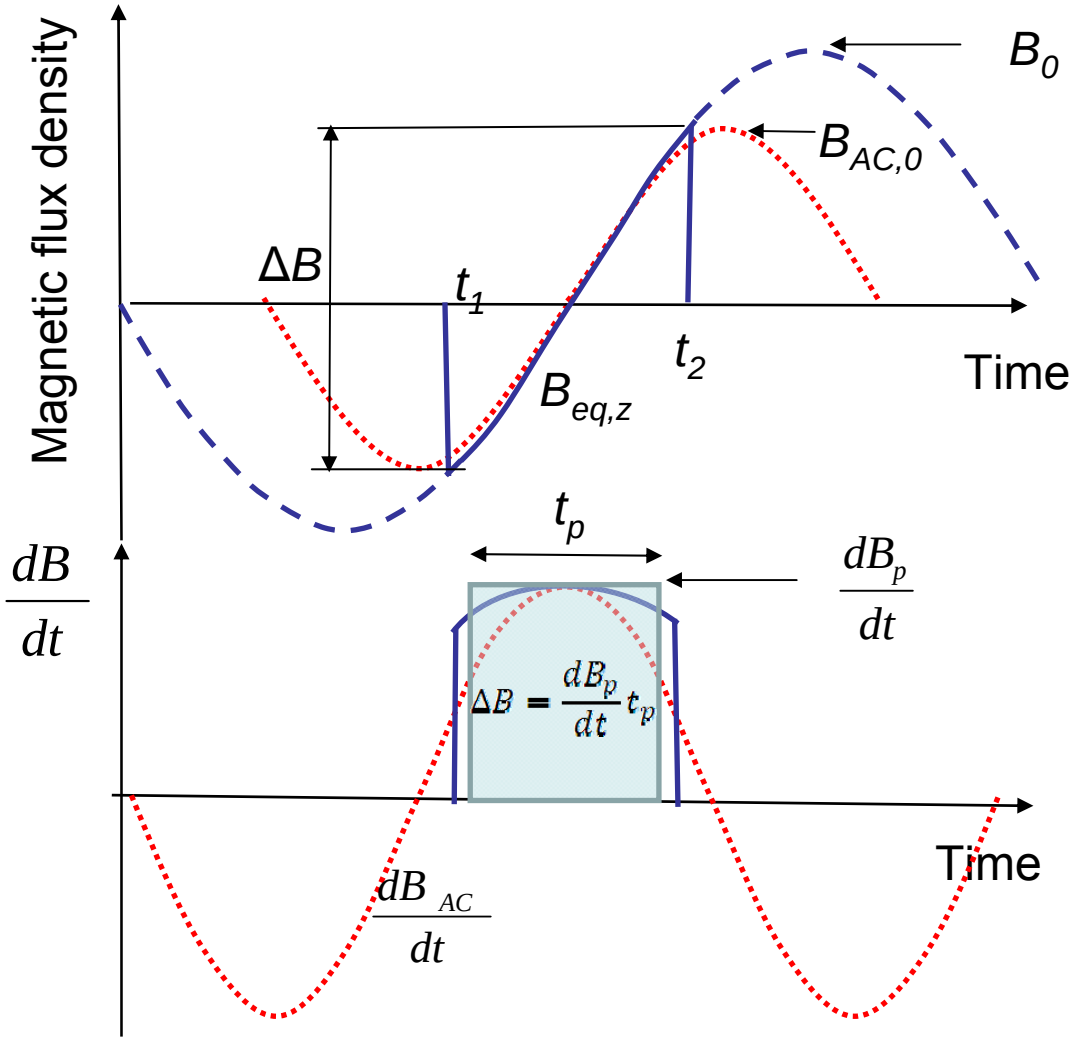


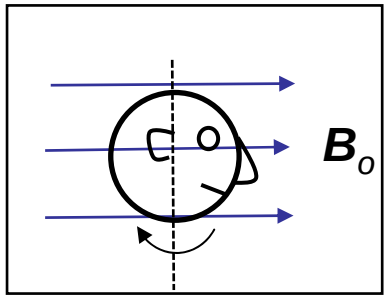


$$B_{AC,o} = \frac{\Delta B}{2}$$



Equivalent AC magnetic field for a head rotating in a static magnetic field





$$B_{AC,o} = \frac{\Delta B}{2}$$

$B_{AC,0} < B_0/2$ for rotation angle $\Delta\Theta < 60^o$

Analytic definition of equivalent fields

$$\frac{dB_{AC}}{dt} = \pi \Delta B f_{AC} \cos(2\pi f_{AC} t)$$

$$f_{AC} = \frac{1}{\pi t_p}$$

$$E_{i,AC} = CF \frac{dB_{AC}}{dt}$$

$$\int E_i \, dt = CF \, \Delta B$$

dB_{AC}/dt =equivalent sinusoidal dB/dt
ΔB = change of the magnetic field during movement
f_{AC} = equivalent frequency
t_p = equivalent pulse duration
$E_{i,AC}$ = equivalent induced sinusoidal E-field
CF = dosimetric conversion factor **0.1 V/m/(T/s)**
E_i = equivalent induced pulsed E-field

Exposure limits for motion induced electric field (draft for open consultation-until 24 May 2012)

Restricted Quantity	Restriction	Frequency range (Hz)	Relevance
Basic restrictions			
ΔB (T)	**2 (during 10 s)**	-	movement
$B_{peak\text{-}to\text{-}peak}$(T)	**2**	< 1	time varying field
Internal electric field (Vm^{-1}_{peak})	0.7/f [1)] 0.07	0 -10 10 –25 [2)]	movement and time varying field
Reference level			
dB/dt (Ts^{-1}_{peak})	1.8/f [1)] 0.22	0 - 8 8 –25[2)]	movement and time varying field

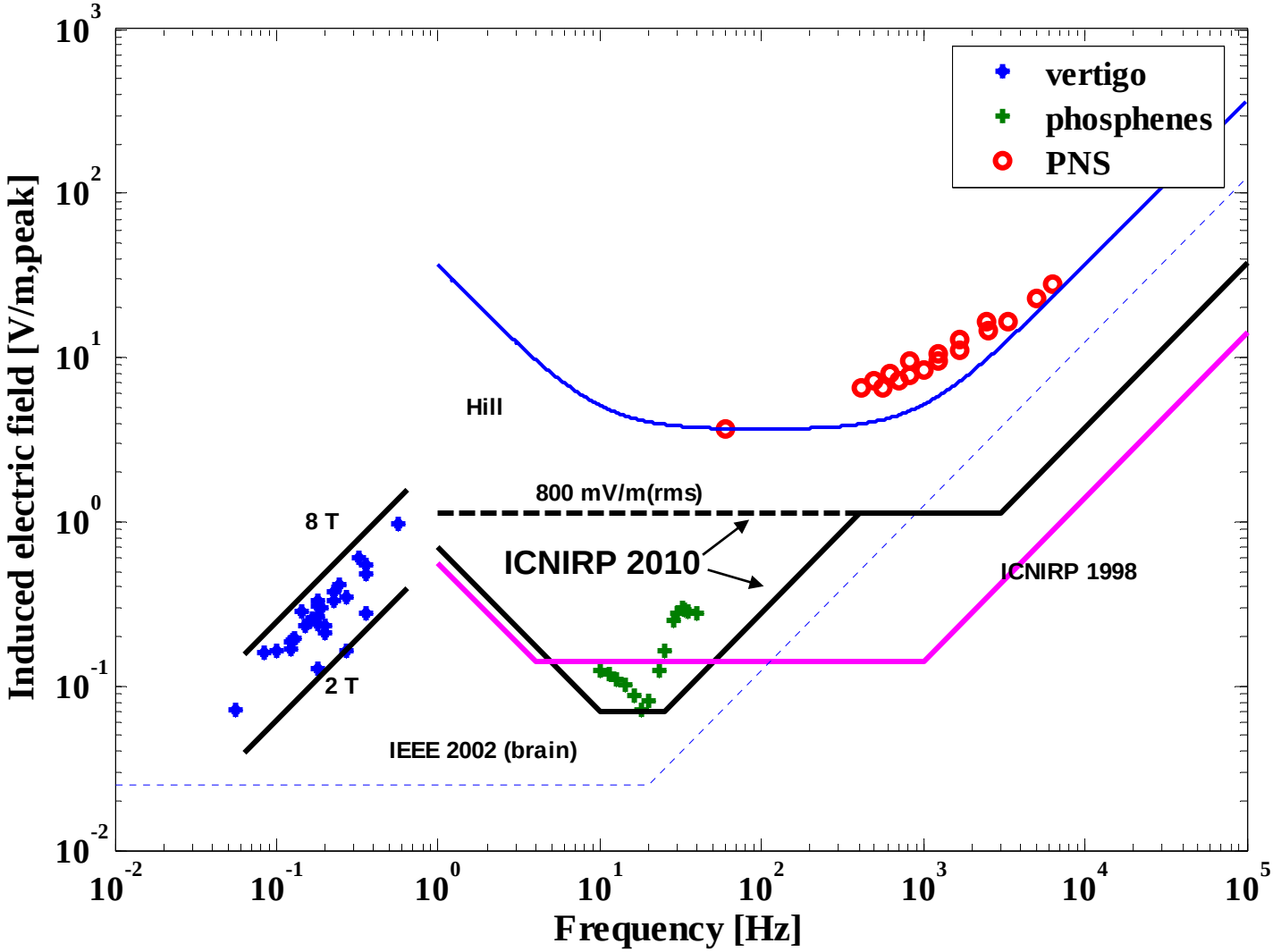
1) f in Hz

2) The reference frequency (ICNIRP 2010) shall be chosen from this frequency range if the restriction value indicated in the same row is used when applying the weighted peak method.

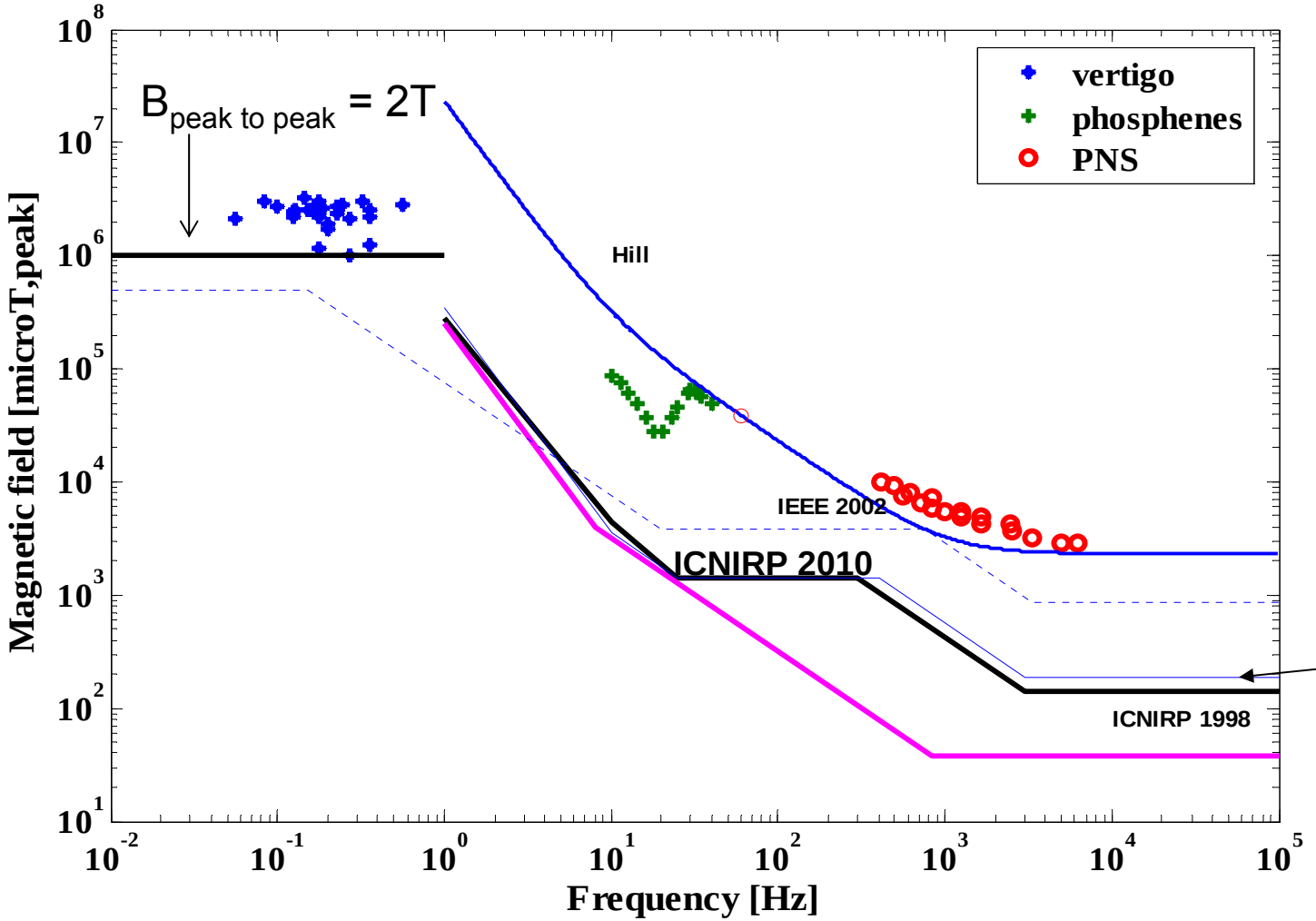
Exposure limits for controlled environment (draft for open consultation-until 24 May 2012)

- Static magnetic flux density < 8T
- Peak induced E-field < 1.1 V/m or peak d*B*/d*t* < 3.5 T/s (CF=0.32 (V/m)/(T/s)

Occupational basic restrictions for magnetic field below 100 kHz

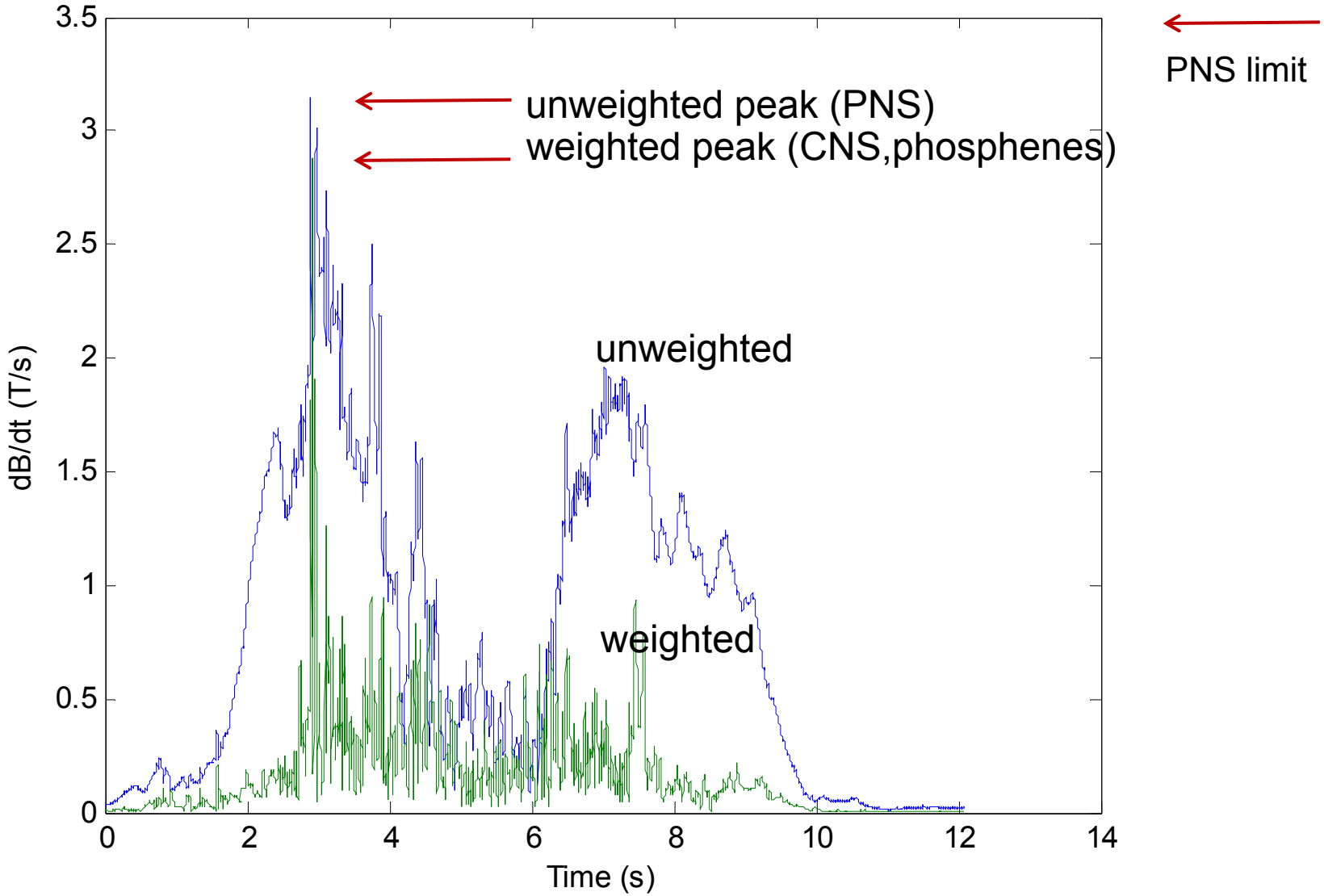


Occupational reference levels for magnetic fields below 100 kHz

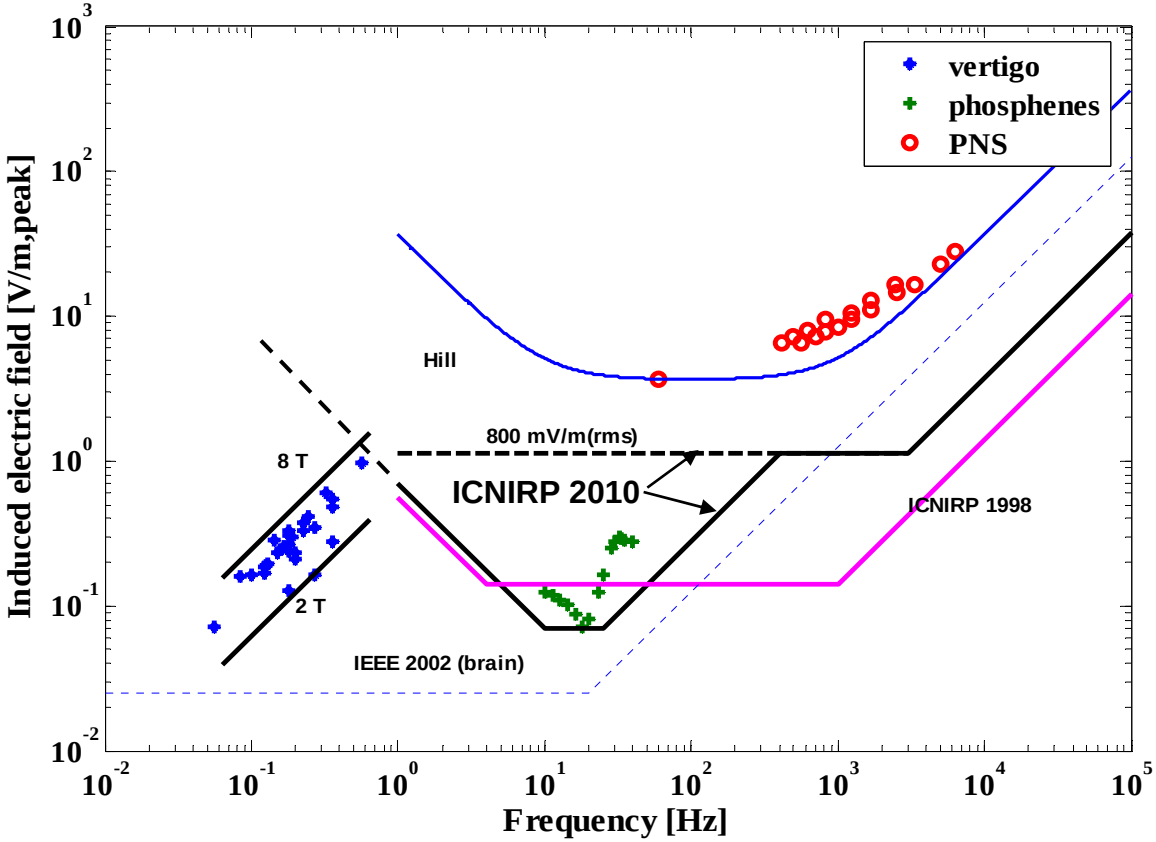


100 mV/m per mT
(50 Hz)

Motion induced dB/dt in the vicinity of a 3 T MRI scanner

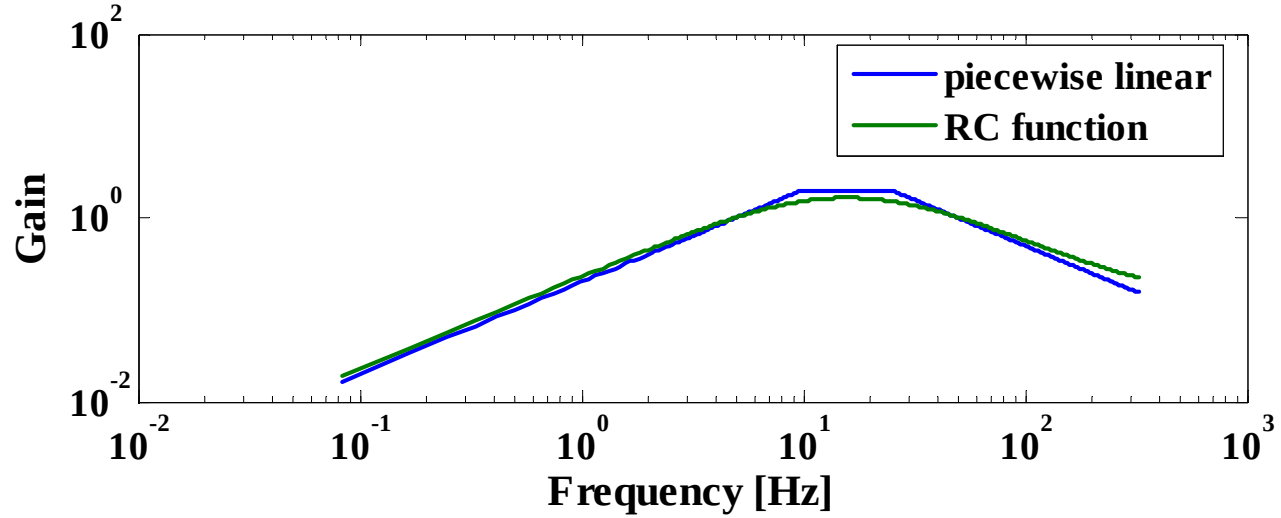


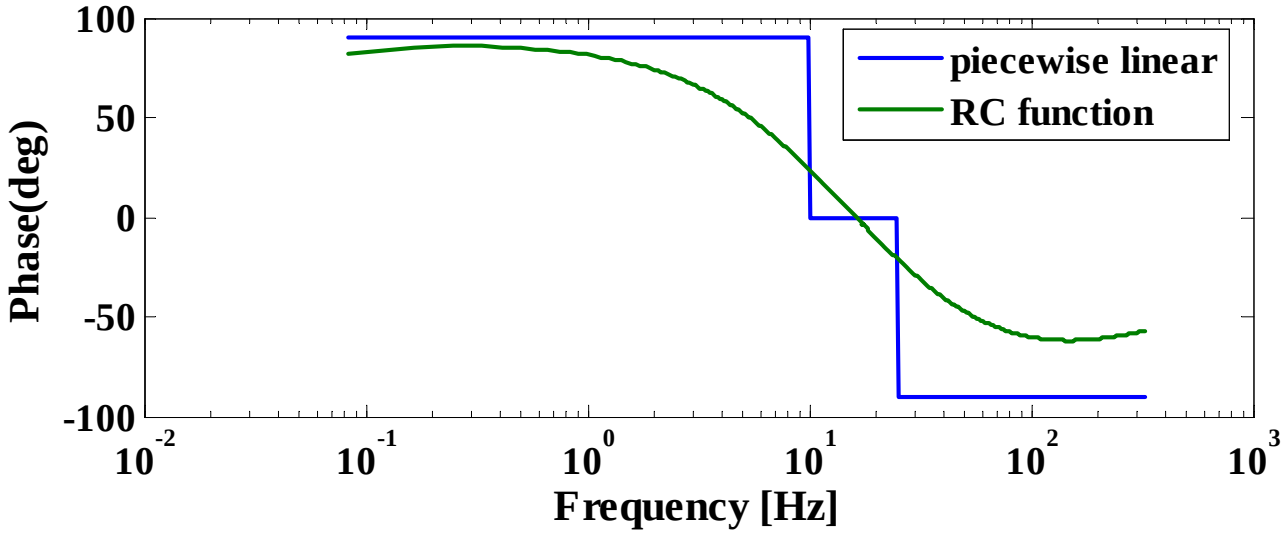
Weighting (filtering) procedure



1) Extend the basic restriction below 1 Hz
2) Invert the besic restriction curve
3) Normalize the basic restriction curve to 1 at an arbitrary reference frequency
4) Limit the filtered peak exposure below the peak basic restriction at the reference frequency

Transfer function of weighting filter for motion induced electric field





Conclusions and recommendations

- Electric fields induced by **motion in a static field** cannot be distinguished from those induced by **exposure to a time varying magnetic field**.

- For **general working conditions** the maximum change of the magnetic flux should be below 2 T and the basic restrictions for the induced electric field should not be exceeded. This protects from vertigo, CNS effects (including phosphenes) and PNS stimulation.

- For **controlled working conditions** the compliance with basic restrictions protects from stimulation. Vertigo can be minimized by controlling movement. If the magnetic field change is less than 2 T, there should be no vertigo.

- Due to their transient non-sinusoidal nature, induced electric field and corresponding dB/dt should be restricted by using the weighted peak method.