BIOLOGICAL AND HEALTH EFFECTS OF ELECTROMAGNETIC FIELDS

Michel Ianoz
Distinguished Lecturer
IEEE EMC Society
E-Mail: michel.ianoz@epfl.ch

Electromagnetic Compatibility, Safety and Biological Effects
• SOURCES OF ELECTROMAGNETIC FIELDS

• A big variety of sources:

• Natural fields:
  - earth magnetic field: 30 - 60 µT

Electromagnetic Compatibility, Safety and Biological Effects
INTRODUCTION

SOURCES OF ELECTROMAGNETIC FIELDS (con’t)

Artificial fields: - in the 70’s: main concern the fields due to power lines and household devices;
- in the 90’s: development of mobile phones the emitting antennas near the human head.

Electromagnetic Compatibility, Safety and Biological Effects
INTRODUCTION

• HOW TO APPROACH THE
  • PROBLEM

• Calculation and measurement ⇒ engineers.
• Biological effects ⇒ biologists + engineers.
• Effects on health ⇒ medical doctors + statisticians
  • (for epidemiological studies).

Electromagnetic Compatibility, Safety and Biological Effects
• CLASSIFICATION

• CW : VLF fields due to power lines (50 - 60 Hz)
• mobile phones : 900 MHz - 2 GHz

• Impulse : lightning, EMP,
  • other short pulses

• Lightning : high energy but the direct thermal effects are much more dangerous for humans than the field.
• CALCULATION METHODS

• 50/60 Hz fields

• For one line:
  Quasi-static problem: the field can be calculated as a static field due to electric charges on the line.
Magnetic field of a three-phase configuration

The total magnetic field results from the superposition of three vectors, each for one phase.

If the current is in x-axis

\[ B_y = -\text{Re} \left[ \sum_{n=1}^{N} \frac{\mu_0 I_n e^{j(\omega t + \alpha_n)} (z - z_n)}{2\pi \left( (y - y_n)^2 + (z - z_n)^2 \right)} \right] \]

\[ B_z = \text{Re} \left[ \sum_{n=1}^{N} \frac{\mu_0 I_n e^{j(\omega t + \alpha_n)} (y - y_n)}{2\pi \left( (y - y_n)^2 + (z - z_n)^2 \right)} \right] \]
• Calculated magnetic field (in µT) for a worker in two positions with respect to a HV line

Electromagnetic Compatibility, Safety and Biological Effects
Induced Current Calculations for Low Frequency EMF Exposure Assessment

The effect of low and intermediate frequency external E&H fields on humans ⇒ to induce currents in the human body.
In this frequency range, the limits of exposure of human bodies expressed in terms of:

- induced currents densities;
- internal electric field.

These are called « basic restrictions ».

They are determined from biological and medical experimentation.

As it is not possible to introduce sensors inside the body to measure these currents it was decided to develop calculation methods.
Current densities of 100 mA/m² can result in reversible biological effects in sensitive tissues (nervous and cardiac).

ICNIRP has defined the basic restrictions taking a security factor with respect to this value which gives an effect:

- factor 10 for professionals ⇒ 10 mA/m².

- factor 50 for the public ⇒ 2 mA/m².
Models based on the following approximating assumptions:

- the real three-dimensional phenomenon (3D) is approximated by a one-dimensional relationship (1D):
  - the human body a cross-section having the shape of a disk;
  - the external field given by a one dimensional wire;
- the human body \(\Rightarrow\) a homogeneous structure;
- the different electrical conductivity of various organs \(\Rightarrow\) not taken into consideration;
- the external field is homogeneous and harmonic at a single frequency.
ICNIRP analytical models for homogeneous fields

These models are based upon the assumptions listed above. The objective of such a simple modelling is to propose a simple method, which gives conservatives values of external fields, with regard to a given level of induced currents.
ICNIRP analytical models for homogeneous fields

The calculation assumes that the exposed body with conductivity $\sigma$ has a circular section of radius $R$ perpendicular to the constant magnetic field.

The induced current at radius $r$ is given by

$$J(r) = \frac{r \cdot \sigma}{2} \cdot \frac{dB}{dt}$$
ICNIRP analytical models for homogeneous fields

For a certain frequency \( J(r) = (\mu_0 \sigma \pi r f).H \)

The induced currents are distributed inside the disk, following rotation symmetry around the central axis of the disk.
For standard values of the typical parameters:
- $f = 50 \text{ Hz}$;
- $H = 1 \text{ A/m}$
- $R = 0.1 \text{ m}$
- $\sigma = 0.4 \text{ S/m}$

This analytical calculation gives a non-realistic uniform distribution.
The distribution can be described by a space-temporal differential equation, the solution of which is obtained by numerical methods.

\[
\frac{1}{\sigma} \nabla^2 \vec{H}_r - \mu_0 \frac{\partial \vec{H}_r}{\partial t} = \mu_0 \frac{\partial \vec{H}_{ex}}{\partial t}
\]

\[\vec{J} = Curl(\vec{H}_r)\]

For the moment only 2-D models have been considered, but 3-D models might be applied is needed in a future development of a standard in preparation by the IEC TC 106.
Disk in the field of an infinite wire

Distribution of $J$ in the disk, for $d = 110$ mm
Disk inside a field created by two close infinite parallel wires with opposite equal currents.

Distribution of $J$ in the disk, for $d = 110$ mm
Disk inside a field created by a circular coil, $d = 110 \text{ mm}$

Current density lines $J$ and distribution of $J$ in the disk
- the hypothesis of constant field is only valid when the distance between the source and the "human disk» becomes important;

- this distance can be estimated to about 10 times the size of the "human disk";

For shorter distances the ICNIRP model can be adapted by using a K factor:

$$ J(r) = K \cdot \mu_0 \cdot \sigma \cdot \pi \cdot r \cdot f \cdot H $$

where \( K = 1 \) for a constant field.
### Factor K values for different configurations

<table>
<thead>
<tr>
<th>Field source characteristics</th>
<th>$J_{m0}/J_{mc}$</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>H=const.(analytical calculation)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>H = const. (numerical calculation)</td>
<td>1</td>
<td>0.9973</td>
</tr>
<tr>
<td>1 wire, d = 110 mm</td>
<td>3.6</td>
<td>0.2280</td>
</tr>
<tr>
<td>2 wires, d = 110 mm</td>
<td>8.4</td>
<td>0.0707</td>
</tr>
<tr>
<td>Coil R = 50 mm, d = 155 mm</td>
<td>7</td>
<td>0.0693</td>
</tr>
<tr>
<td>Coil R = 10 mm, d = 115 mm</td>
<td>14.9</td>
<td>0.0280</td>
</tr>
</tbody>
</table>

$J_{m0}$ - local current density for simplified analytical calculation;

$J_{mc}$ - current density obtained from a numerical calculation which takes into account the non-homogenous disk structure.
Field intensities corresponding to the basic restrictions

SAFETY IN E AND B FIELD: REFERENCE LEVELS

By courtesy of Prof. W. Van Loock

Electromagnetic Compatibility, Safety and Biological Effects
Several ways to decrease the field intensity:

- increase the height of the line;
- optimize the phase arrangement;
- symmetrical phase arrangement;
- make the line compact;
- increase the voltage to reduce the current;

If all these solutions have been used, the only way is to put sensitive buildings at larger distances.
Protection against E&M fields

Optimization of the phase arrangement

a) Symmetrical arrangement

```
A • • • • • •
B • • • • • •
C • • • • • •
```

b) Optimum arrangement

```
A • • • • • •
B • • • • • •
C • • • • • •
```

Electromagnetic Compatibility, Safety and Biological Effects
Protection against E&M fields

Phase compact arrangement

Electromagnetic Compatibility, Safety and Biological Effects
Protection against E&M fields

Protection inside buildings: LV power substations in a building.
Are mobile phones safe?

Research intensifies as the public grows wary of one of its favorite communications tools

EMCO Society

Electromagnetic Compatibility, Safety and Biological Effects
• Field measurements inside the head

Phantoms simulating the tissue are used for measurements. Very fine sensors are introduced inside the phantom.
• Model for numerical calculation

- the antenna and the metallic box of the phone are modelized with $E_{\text{tang}} = 0$
- for the arm and the head the model takes into account the dielectric properties of the tissues.
• Results:

- the Specific Absorbtion Rate (SAR).

- temperature increase;

Temperature elevations of about 1 degree have been found.
• Presence of other frequencies:

  • modulation frequencies of 2, 8, 217, 1734 Hz + harmonics;

  • The Time Division Multiple Access (TDMA) has a $f = 217$ Hz;
  • The Discontinuous Transmission DTX) component produced when the user is connected but does not speak has a $f = 2$ Hz;

These ELF components:

• pulse the RF carrier wave;
• generate ELF magnetic field via battery;
Recent study on the effects of cell phones on regional cerebral blood flow at ETH Zurich

Effects:
- modifies brain physiology and sleep behavior;
- increases regional cerebral blood flow;

Exposure conditions:
- SAR: 1 W/kg;
- handsets: 1 time slot/8.
- base stations: 7 time slots/8;
Recent study on the effects of cell phones on regional cerebral blood flow at ETH Zurich

Effect on the electroencephalogram (EEG);
- the black bar indicates significant differences between EMF exposure and sham exposure.
• Base stations

In order to respect limits:
Cellular concept of the base station arrangement on a given territory.
• BIOLOGICAL EFFECTS

• Due to:

• ELF or LF fields: a few Hz to 500 Hz
• HF fields: 900 MHz to a few GHz;
• Biological effects due to LF electric field:
  • 1) Electrostatic forces at the body surface ⇒ vibration of the hair system of humans and animals for $E > 12$ kV/m
  • 2) Microdischarges between the clothes and the skin.
Biological effects due to 50/60 Hz

- Biological effects due to the electric field:
  - 3) Effects on pacemakers:
  - Experimental studies in HV laboratories
• Effects on pacemakers:
• Pacemaker implementation modelling
Biological effects due to the magnetic field:

The melatonin: produced by the pineal gland.

Normal day to night variation of the melatonin.
• Effect of light on the melatonin

• One hour of light exposure during the night.
• Light intensity:
  • A : 3000 lux
  • B : 1000 lux
  • C : 500 lux

• A very clear effect ⇒ decrease in the melatonin.
Biological effects due to 50/60 Hz

Chronic 50 Hz magnetic field

Pineal gland: reduced melatonin production

Ovary: increased estrogen production
Pituary gland: increased prolactin production

Increased turnover of breast epithelial stem cells at risk

Increased mammary carcinogenicity
Influence of LF electromagnetic fields on the development and the molecular biology of the moss *Physcomitrella patens*

- Project participants:
  - Prof. J-P. Zrŷd, Ecological Institute - University of Lausanne
  - Dr. F. Rachidi, Prof. M. Ianoz, Power Systems Laboratory - Swiss Federal Institute of Technology - Lausanne
  - Dr. Elena Comino and students - Politecnico di Torino
Why vegetals?
• Originality with respect to other tests
• Simple structures

Choosed vegetals:
• A moss
• Psychomitrela patens

Why? The moss behaviour well known by the biologists
Biological effects due to 50/60 Hz

Experimental arrangement at 50 Hz

\[ V_{\text{max}} = 80 \text{ kV}; \quad E_{\text{max}} = 400 \text{ kV/m} \quad I_{\text{max}} = 8 \text{ A}; \quad B_{\text{max}} = 1.2 \text{ mT} \]

Electromagnetic Compatibility, Safety and Biological Effects
Biological effects due to 50/60 Hz

Coils arrangement

Temperature: 25 °C
Lighting: 16h/day
Duration: 2 to 3 weeks

Fields: 50Hz and DC
50 Hz values:
0 - 0.6 - 0.9 - 1.2 mT

Electromagnetic Compatibility, Safety and Biological Effects
Biological effects due to 50/60 Hz

Mosses in plastic boxes

Aspect of mosses growth after a different number of days.
Biological effects due to 50/60 Hz

Normal and exposed moss aspect

**Left**: aspect of the moss during normal development.

**Right**: aspect of the moss with partial dead cells after MF exposure.
A longer time statistic has shown

<table>
<thead>
<tr>
<th>No. Exp.</th>
<th>Control</th>
<th>6A/DC</th>
<th>6A/16Hz</th>
<th>6A/50Hz-1.07</th>
<th>6A/50Hz-1.2</th>
<th>6A/400Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100%</td>
<td>82%</td>
<td>87%</td>
<td>93%</td>
<td>-</td>
<td>107%</td>
</tr>
<tr>
<td>2</td>
<td>100%</td>
<td>77%</td>
<td>91%</td>
<td>82%</td>
<td>-</td>
<td>99%</td>
</tr>
<tr>
<td>3</td>
<td>100%</td>
<td>98%</td>
<td>78%</td>
<td>138%</td>
<td>-</td>
<td>167%</td>
</tr>
<tr>
<td>4</td>
<td>100%</td>
<td>84%</td>
<td>75%</td>
<td>114%</td>
<td>-</td>
<td>131%</td>
</tr>
<tr>
<td>5</td>
<td>100%</td>
<td>44%</td>
<td>56%</td>
<td>58%</td>
<td>-</td>
<td>108%</td>
</tr>
<tr>
<td>6</td>
<td>100%</td>
<td>74%</td>
<td>74%</td>
<td>97%</td>
<td>-</td>
<td>119%</td>
</tr>
<tr>
<td>7</td>
<td>100%</td>
<td>80%</td>
<td>66%</td>
<td>112%</td>
<td>-</td>
<td>141%</td>
</tr>
<tr>
<td>8</td>
<td>100%</td>
<td>99%</td>
<td>65%</td>
<td>75%</td>
<td>77%</td>
<td>119%</td>
</tr>
<tr>
<td>9</td>
<td>100%</td>
<td>72%</td>
<td>81%</td>
<td>68%</td>
<td>69%</td>
<td>122%</td>
</tr>
<tr>
<td>10</td>
<td>100%</td>
<td>106%</td>
<td>75%</td>
<td>74%</td>
<td>75%</td>
<td>116%</td>
</tr>
<tr>
<td>11</td>
<td>100%</td>
<td>120%</td>
<td>81%</td>
<td>89%</td>
<td>80%</td>
<td>132%</td>
</tr>
</tbody>
</table>

No influence  Delayed growth  Accelerated growth
A new tool: use of fractal characterization

Non-exposed plant
Fractal dimension = 1.64

Plant exposed at 50 Hz
Fractal dimension = 1.51
Experiment at 900 MHz

Experiments performed on:

-- the moss *Physcomitrella patens*
- the nematode *Coenorhabditis elegans*.

- Field source: a TEM cell

\( f = 900 \, \text{MHz} \)
\( E = 1000 \, \text{V/m} \)
Experiment at 900 MHz

EXPERIMENTAL DISPOSAL

Ventilator → TEM cell → Generator

- Generator: 900 MHz
- Amplifier: 70 W
- the HF criteria is usually the SAR.

**Methods for the SAR evaluation:**

- direct temperature measurement
- electric field measurement using sensors

Due to the *P. patens* configuration and the very tiny size of the *C. elegans*, none of the above methods is really suitable.
WORKING METHOD

- *Physcomitrella patens* cultivation in Petri dishes (6 days);

- Chlorophyll fluorescence measure with PLANT EFFICIENCY ANALYZER before the exposure to the field:

Moss exposure to the EMF;

- Chlorophyll fluorescence measure after the exposure; ($T_{exp} = 24h; 48h$).

- Data processing with BIOLYZER.
Experiment at 900 MHz

Radar plot

$T_{\text{exp}} = 24 \text{ h}$

--- control
--- EMF

............ $T_0$

...... $T_0$
Experiment at 900 MHz

Radar plot

\[ T_{\text{exp}} = 48 \text{ h} \]
The EM field exposure resulted in:

1. *Decrease* of performance index (PI)
2. *Increase* of inactive reaction centers (RC)
3. *Decrease* of electron transport (ET)

Perturbation of *Physcomitrella patens* photosynthetic activity after exposure to high frequency EMF

Method based on fluorescence measure is non invasive and useful to test the biological effect of environmental stress.
Another experimental approach:

Use of the nematode *Caenorhabditis elegans*.

Advantage:
- completely known genome.
Preliminary results for C. elegans

Fractal dimension associated to the C. elegans mobility for 20 Petri dishes after a 3 days exposure.
Experiment at 900 MHz

Fractal dimension associated to the C. elegans mobility

After 1 minute
Fractal dimension 1.382

After 3 minutes
Fractal dimension 1.626

Use of an iterative filter
PRELIMINARY CONCLUSION

- need to provide the public and industry with more knowledge about the possible effects of cellular phones.

- thermal effects are known to exist.

- are there also other side effects?

- the project is intended to open roads for future developments.
HEALTH EFFECTS
Health effects

Can be evaluated in three ways:

1) Epidemiological studies

2) Experiences on animals

3) Correlation of biological and health effects.

The first two methods have been used, the 3rd one begins now.
Epidemiological studies

First studies of this type: the Wertheimer & Leeper study of 1979 and Savitz et al. of 1988 which seem to show evidence of higher leukemia rate for children living in the proximity of HV power lines.

Further epidemiological studies could not clearly confirm this result:

- in Scandinavian countries;
- EDF + Hydro-Québec + Ontario Hydro;
- american and swedish studies.
Health effects

Relative risk (RR) in epidemiological studies:

- $RR < 1.5$ non significative risk
- $RR = 2 - 3$ a risk difficult to evaluate

Example: RR for a heavy smoker = 40

The epidemiological studies gave usually for the electromagnetic fields a $RR = to 1.5 - 3$. 
Swedish Study on *Childhood cancer and ELF Magnetic Fields*

*Population located within 300 m from 220 and 400 kV lines during the period 1960 to 1985.*

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>&lt; 0.1 µT</th>
<th>0.1 - 0.19 µT</th>
<th>&gt; 0.2 µT</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. RR</td>
<td>No. RR.</td>
<td>No. RR.</td>
<td>No. RR.</td>
</tr>
<tr>
<td>All cancer</td>
<td>117 1</td>
<td>12 1.5</td>
<td>12 1.1</td>
</tr>
<tr>
<td>Leukaemia</td>
<td>27 1</td>
<td>4 2.1</td>
<td>7 2.7</td>
</tr>
<tr>
<td>Brain tumors</td>
<td>29 1</td>
<td>2 1</td>
<td>2 0.7</td>
</tr>
<tr>
<td>Lymphomas</td>
<td>16 1</td>
<td>1 0.9</td>
<td>2 1.3</td>
</tr>
</tbody>
</table>

*Only Leukaemia RR = 2.7 for B > 0.2 µT indicate a very small possible adverse effect.*
Review of child leukemia studies related to power lines

Wertheimer & Leeper 1979
Fulton et al. 1980
Tomenius 1986
Tomenius 1986
Savitz et al. 1988
Savitz et al. 1988
Coleman et al. 1990
Myers et al. 1990
Myers et al. 1990
London et al. 1991
London et al. 1991
Feychting & Ahlboom 1992
Feychting & Ahlboom 1992
Feychting & Ahlboom 1992
Linet et al. 1997
Health effects

Ahlbom et al. Study on child leukemia: 4 categories:
- < 0.1 µT ⇒ used as non-exposed group
- 0.1 – 0.2 µT
- 0.2 – 0.4 µT
- > 0.4 µT mean RR = 2 (1.27 – 3.13)

Field mean values on 24 or 48 hours, during the year before the illness was declared.

The International Center on Cancer Research (ICCR) has adopted for the moment the 0.4 µT value as cut off value.
Impossible to chose a higher value because populations exposed to B > 0.4 µT are too small to be statistically significative.
Health effects

Why do the epidemiological studies give approximate results:

- it is impossible to separate other factors like pollution;
- field values in residential environments ⇒ very low (of the order of 0.1 μT)
- lack of toxicology data to prove the potential cancerogenic effect of the magnetic field.

Epidemiology is not an experimental science but a statistical approach ⇒ low statistical evidence.

Electromagnetic Compatibility, Safety and Biological Effects
Effects on health

Animal studies on 50/60 Hz field effects on induced cancer:

Electromagnetic Compatibility, Safety and Biological Effects
STANDARDIZATION AND LIMITS
Not any IEC or CENELEC approved standard giving limits for any kind of electric or magnetic fields.

TC106 of IEC has the task to produce standards on «Measurement methods for EM fields».

Official documents on limits have been published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP).
Maximum E-field values at $f = 50$ Hz for human exposure

- Short time (kV/m) 8 or 24 hours (kV/m)
- ICNIRP
  - profesional 10
  - public 5
- ORNI
  - (Switzerland)
  - immition value for public 5
• Maximum B-field values at $f = 50$ Hz for human exposure
• Short time ($\mu T$) 8 or 24 hours ($\mu T$)
• ICNIRP
• occupational 500
• public 100
• ORNI for public
• (Switzerland)
• immition 100
• emission 1

Electromagnetic Compatibility, Safety and Biological Effects
**PUBLIC HEALTH AND STATIONARY ANTENNAS**

<table>
<thead>
<tr>
<th>SAR (W/kg)</th>
<th>FREQ. (MHz)</th>
<th>POWER-FLUX W/m²</th>
<th>E-FIELD V/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF 50</td>
<td>900</td>
<td>4,5</td>
<td>41</td>
</tr>
<tr>
<td>public</td>
<td>1800</td>
<td>9</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>2450</td>
<td>10</td>
<td>62</td>
</tr>
<tr>
<td>HF 4</td>
<td>900</td>
<td>1,1</td>
<td>21</td>
</tr>
<tr>
<td>public</td>
<td>1800</td>
<td>2,3</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>2450</td>
<td>2.5</td>
<td>31</td>
</tr>
</tbody>
</table>

BELGIUM

*Electromagnetic Compatibility, Safety and Biological Effects*
## Public Health and Stationary Antennas

<table>
<thead>
<tr>
<th>Country/ freq.</th>
<th>900 MHz</th>
<th>1800 MHz</th>
<th>2,45 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU, WHO</td>
<td>4,5 W/m²</td>
<td>9 W/m²</td>
<td>10 W/m²</td>
</tr>
<tr>
<td>Belgium (F)</td>
<td>1,13</td>
<td>2,25</td>
<td>2,3</td>
</tr>
<tr>
<td>Italy (G)</td>
<td>0,1</td>
<td>0,2</td>
<td>0,2</td>
</tr>
<tr>
<td>Switzerland</td>
<td>0,042</td>
<td>0,095</td>
<td>0,1</td>
</tr>
<tr>
<td>Belgium (W)</td>
<td>0,024</td>
<td>0,095</td>
<td>0,1</td>
</tr>
<tr>
<td>Paris</td>
<td>0,024</td>
<td>0,095</td>
<td>0,1</td>
</tr>
<tr>
<td>Austria (S)</td>
<td>0,001</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

By courtesy of Prof. W. Van Loock

---

Electromagnetic Compatibility, Safety and Biological Effects
• The low emission value based on the precautionary principle.

• The precautionary principle says that lack of certainty, given the current scientific and technological knowledge shall not delay effective and proportionate actions to prevent hazards, taking into account cost-benefit considerations.
• Examples of the use of the precautionary principle:

• The laws and measures concerning Genetically Modified Organisms.

• Example of cost-benefit consideration:

• Cost of HV power line mitigation in Italy a few billion USD
• Benefit: 1 child leukemia case/year.
• Examples of the use of the precautionary principle:

• Children garden on the ground floor of a building over a train track in the town of Geneva.

• Magnetic field measurements:

• 2.4 $\mu$T average value, with peak values during short periods of 12 $\mu$T.

• Municipality decision: move the children garden.