SWINBURNE UNIVERSITY OF TECHNOLOGY

EMF Science and the Development of the ARPANSA ELF Standard

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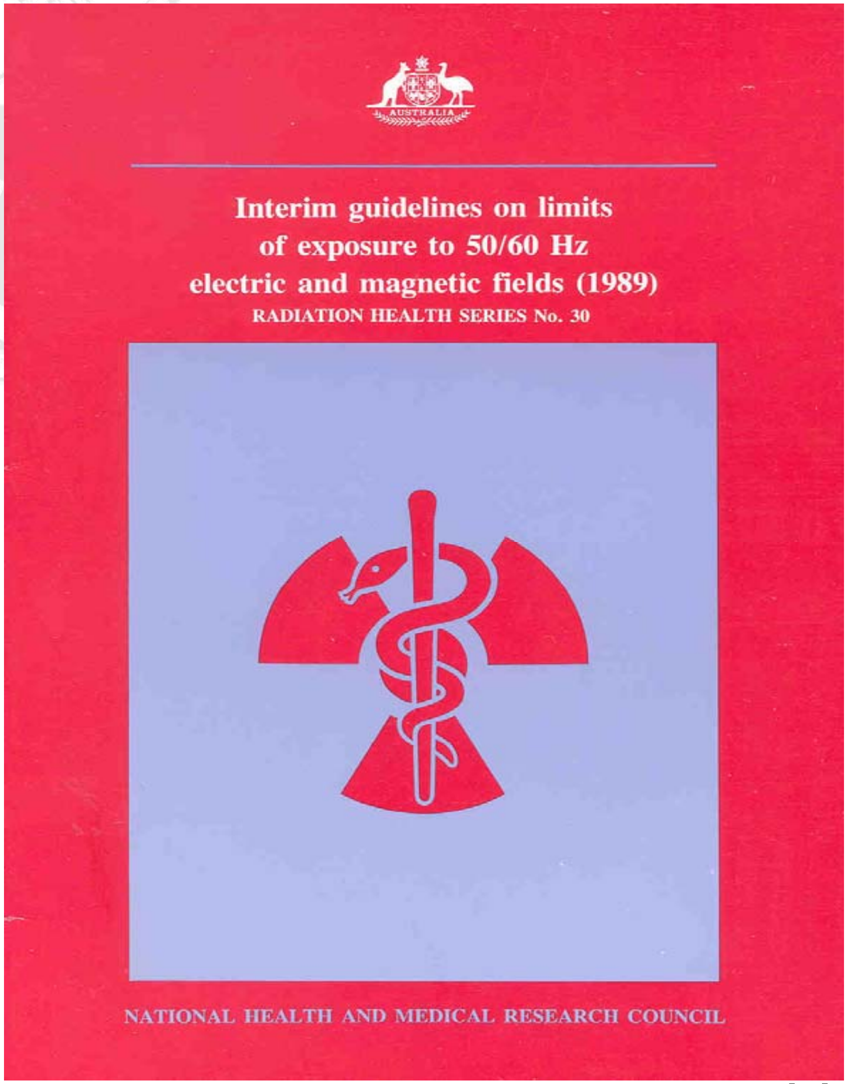
Synopsis

- **Background**: the task of the ARPANSA ELF Standard Working Group (WG)
- **Physiological effects** underlying basic restrictions: review of literature
- **Safety margins**: rationale
- Derivation of practical **Reference Levels** from basic restrictions
- **Regulatory impacts** for national standards adoption
- Timetable

Radiation Health Committee task

- Aim for WG: develop a **scientific limits**-based restrictions for human ELF exposure; to ensure protection against **established adverse** health effects
- Affected parties: mainly industries producing/using high power/current electrical apparatus - **not just 50/60 Hz**.
- Consideration of separate **occupational** and **general public** exposure categories
- Range: 0 – 3 kHz. Already an ICNIRP-based **RF standard** 3 kHz – 300 GHz (RPS 3)

Aim: replace 1989 Guidelines



What has the Task Group done?

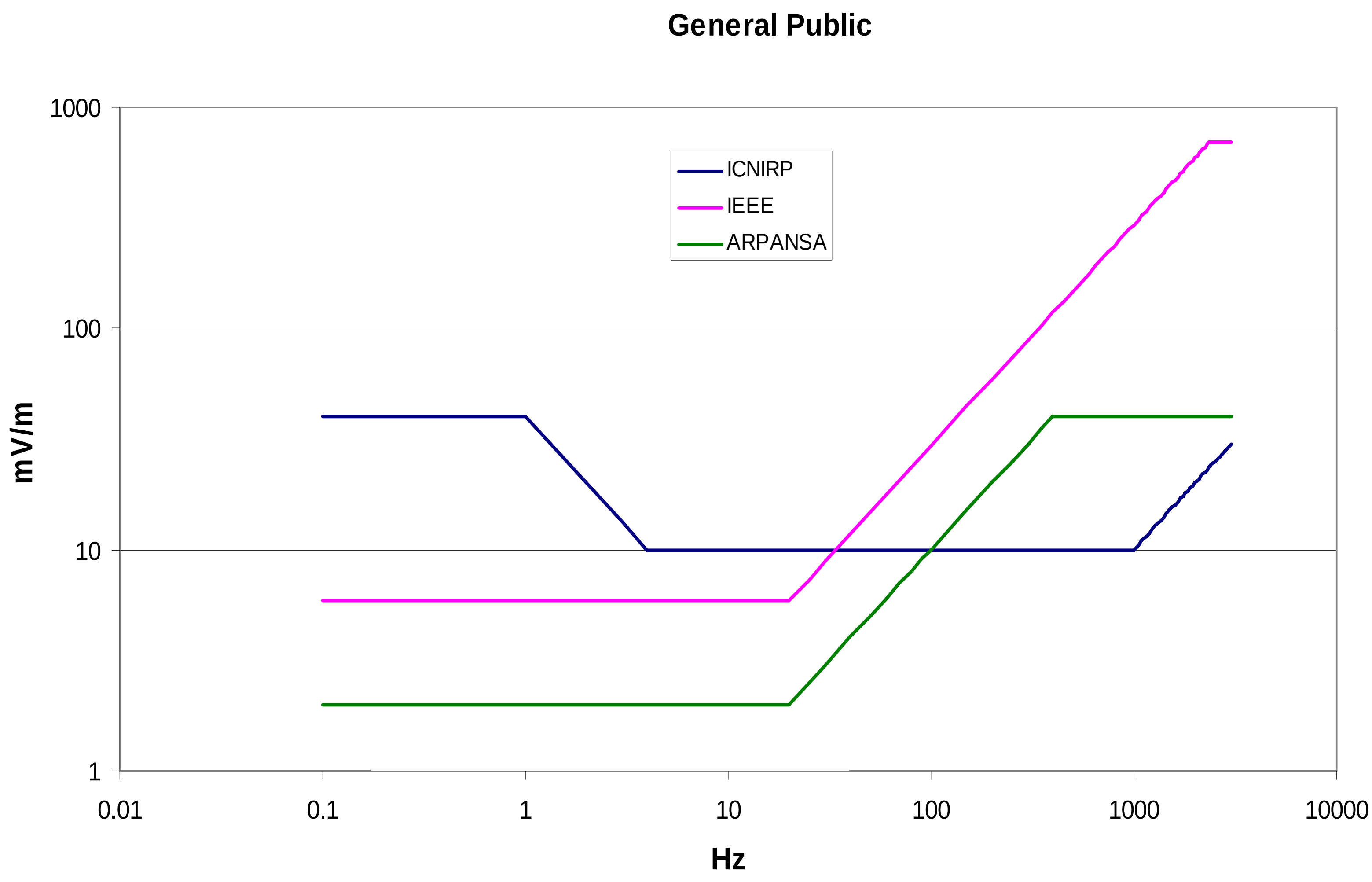
- **Wide divergence** between existing standards/guidelines noted: reasons identified and progress made on more precise and up to date rationale
- Research data from mathematical modelling, published early 2005, forced re-think on way of deriving Reference Levels for **Electric** fields (**Magnetic** fields also)
- Current draft has set of limits different from **both** ICNIRP & IEEE
- Consulted with international & local experts

Basic Restrictions (BRs)

- Both IEEE & ICNIRP have BRs in tissue to avoid **retinal phosphenes** and **peripheral nerve stimulation**
- ICNIRP based on **current density** (J: mA/m^2) and IEEE on tissue **electric field** (E: mV/m)
- Comparison via $J=\sigma E$: Assume tissue conductivity $\sigma = 0.2$ S/m
- Frequency dependence of the two approaches quite different

Basic Restrictions (BRs)

- (ICNIRP converted via σ = 0.2 S/m)



ARPANSA (Australian) BRs

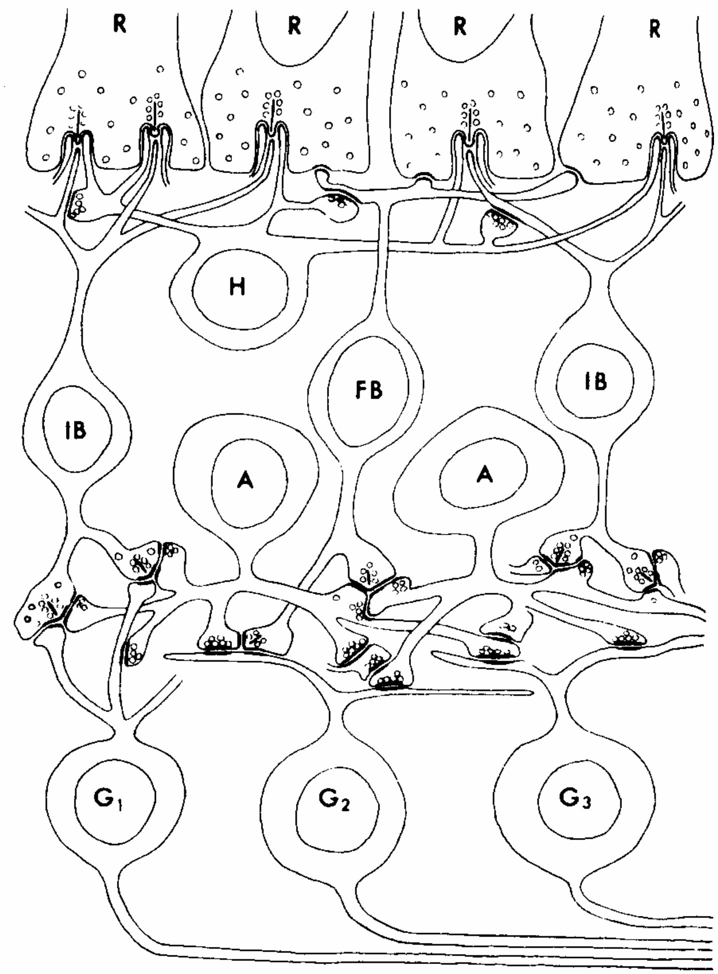
- Based on estimates of thresholds for (a) electro- and magneto-phosphenes; (b) peripheral nerve stimulation
- For (a), most sensitive frequency 20 Hz, threshold assumed to vary as f/20 above this frequency (& remain flat below)
- For (b), similar shape assumed, with threshold rising as f/f_0, where f_0 is determined by the chronaxie (time constant) of peripheral nerves
- Similar approach to IEEE

Biophysics: the phosphene

- ‘See stars’ when the eyeball is rubbed or poked – pressure phosphene
- Get similar sensations when eyeball is stimulated by electrical current
- Seems to originate within retinal tissue rather than optic nerve (but can also get similar sensations by stimulating visual cortex – basis of ‘bionic eye’)
- Retina is designed to detect light: these other stimuli are termed ‘inadequate stimuli’ because they lead to an abnormal response

Architecture of retinal cells

- Close packing of cells
- High connectivity
- Little myelination
- Radial currents most effective for stimulation
- 'Ribbon synapses' are very specialised
- Number of reasons to expect this tissue to be the most sensitive to ELF



Source: Aidley, The Physiology of Excitable Tissues

Phosphenes: Electrophosphenes

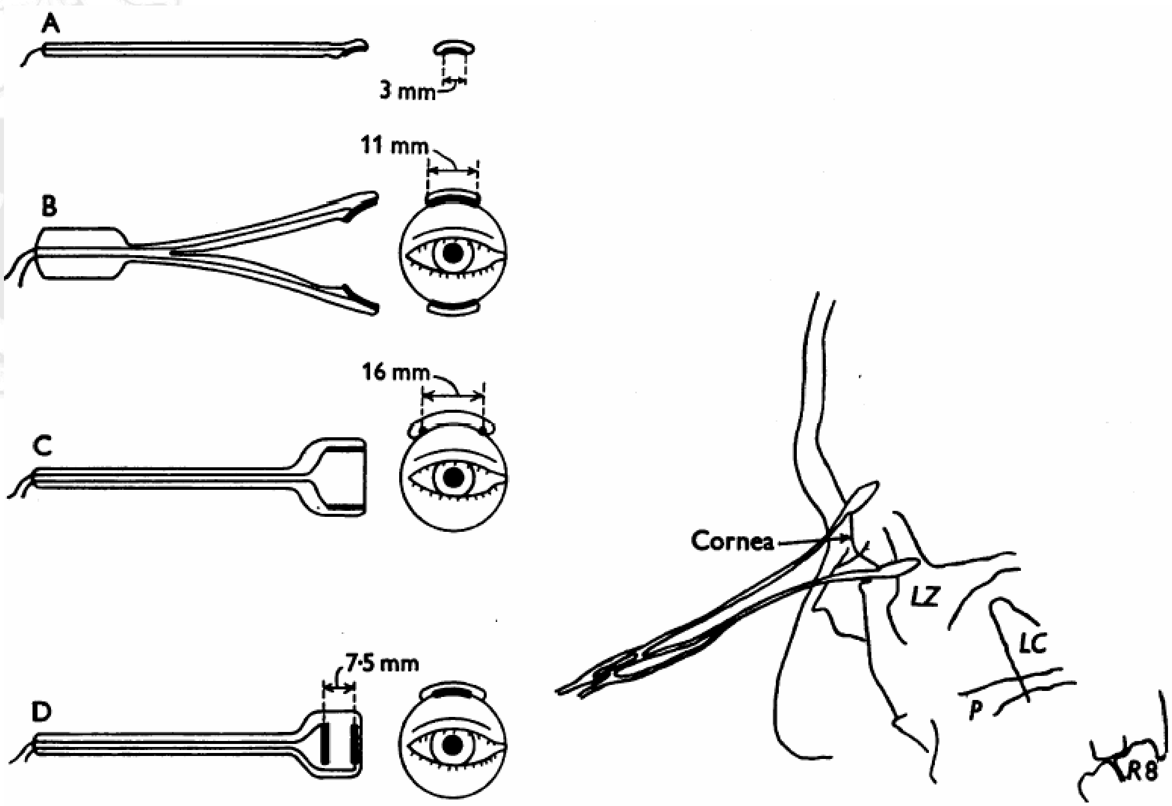
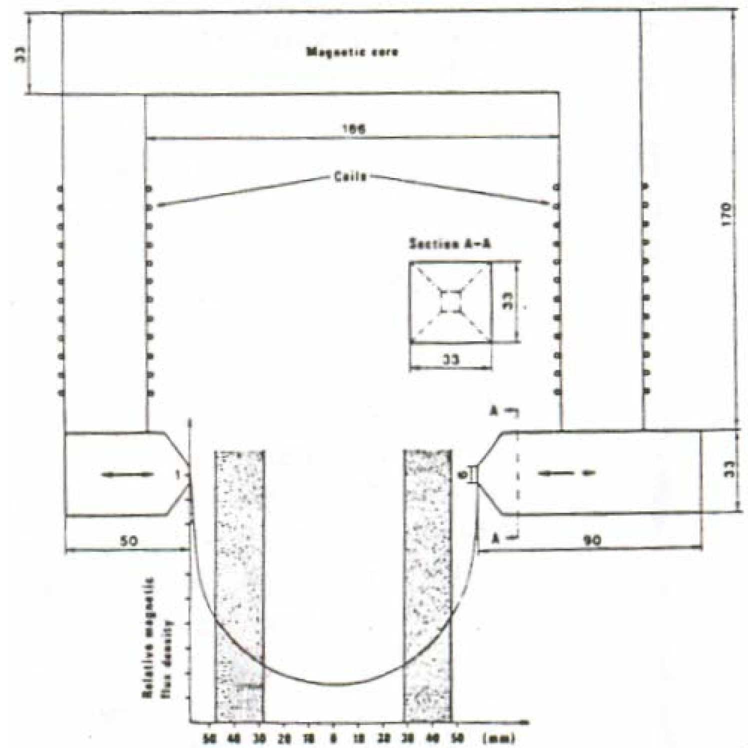


Fig. 1 Fig. 2

50 Hz currents applied across eyeball as shown

From Brindley, J Physiol 127:189 (1955)

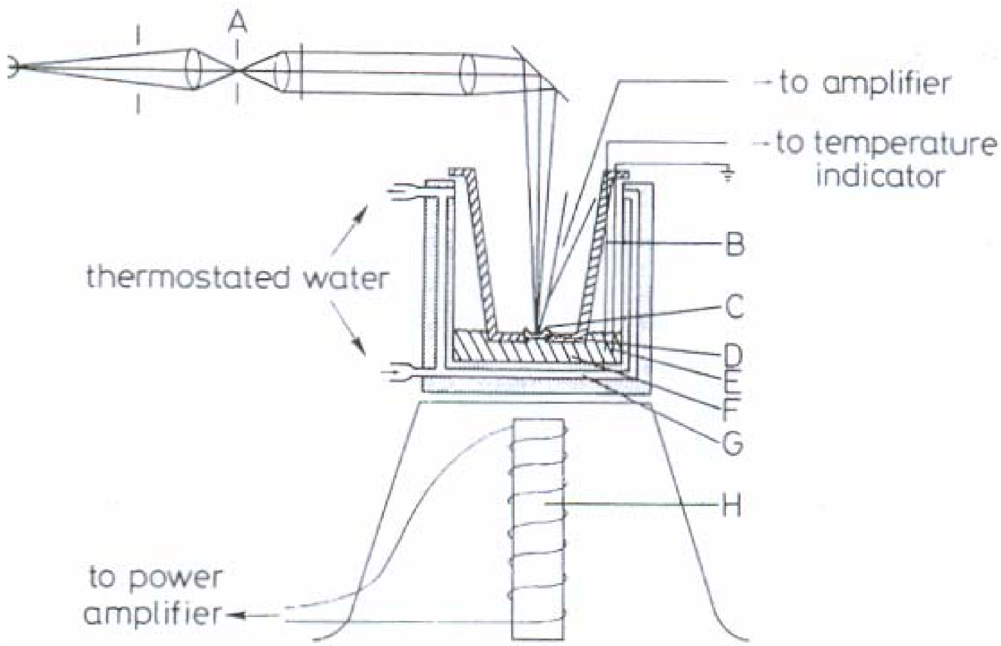
Phosphenes: Magnetophosphenes



Head inserted between pole-pieces of electromagnet: note estimate of magnetic flux density with distance

From Lövsund et al. Med Biol Eng Comput 18:326 (1980)

Phosphenes: Magnetophosphenes



Isolated frog retina: measure direct electrical responses

From Lövsund et al. Med Biol Eng Comput 19:679 (1981)

Magneto & Electrophosphenes

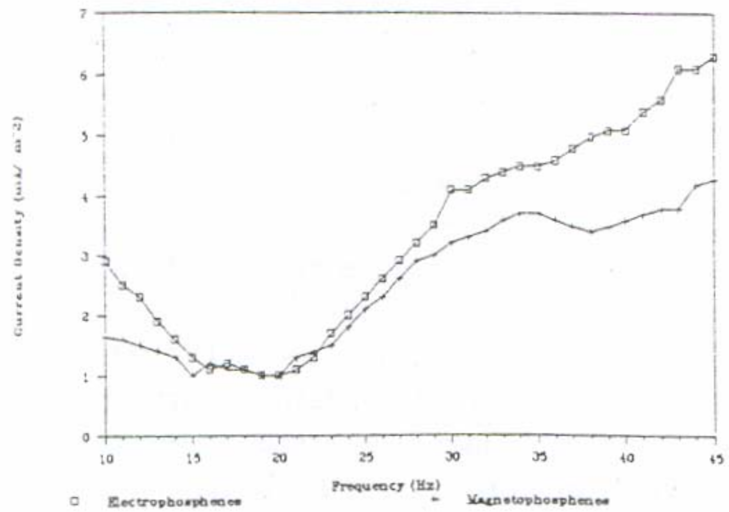


Figure 3. Estimates of electrically-induced and magnetically -induced current densities in the eyeball. Electrophosphene data is normalized (data from 26): see also 123.

Both phenomena seem to follow similar frequency dependencies if the fields are converted to induced current density: but is the minimum value the same for both phenomena?

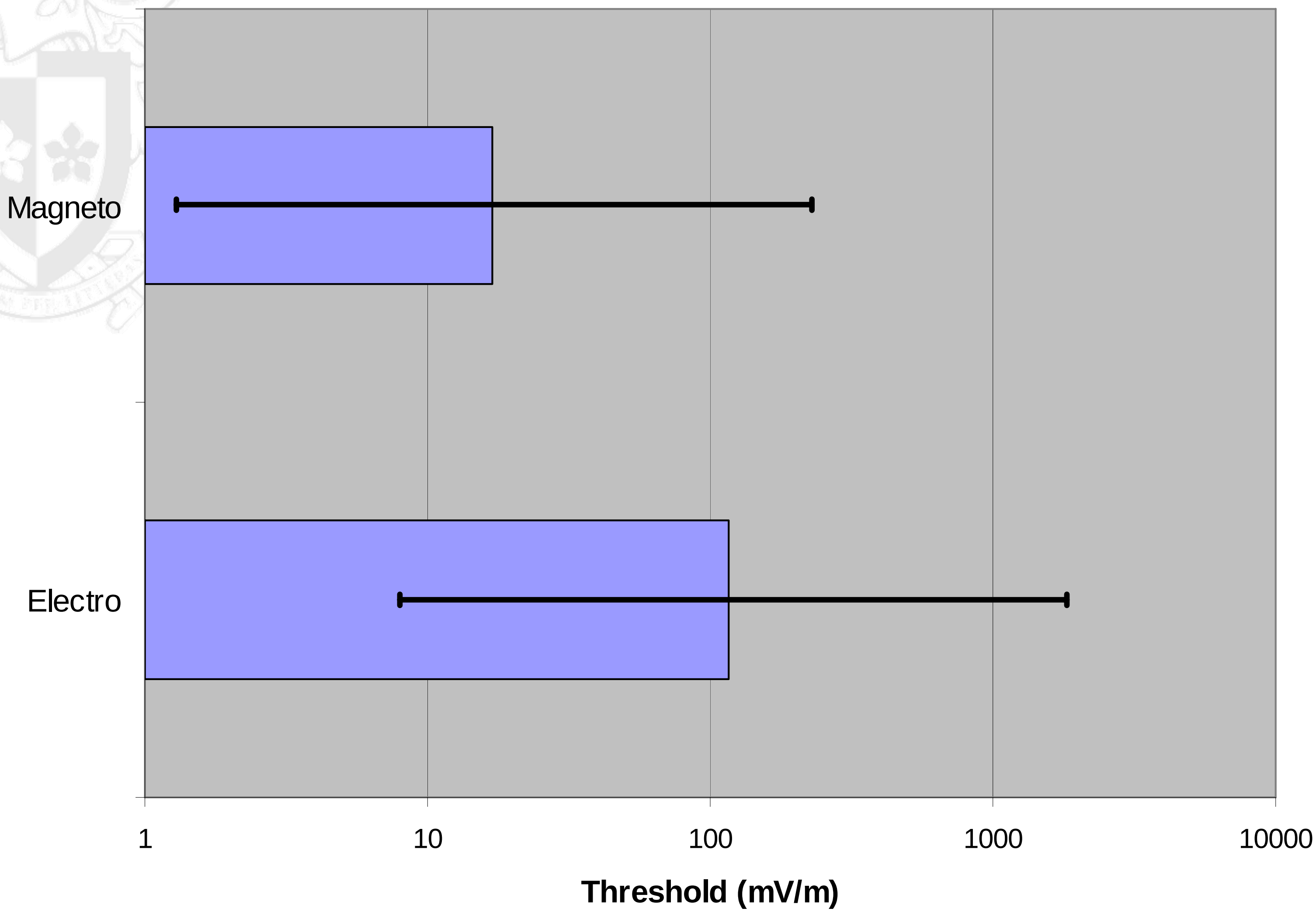
Electro-phosphenes: 20 Hz Thresholds

Author(s)	Basic finding @ 20 Hz (uos)	Assumptions made	mV/m
Taki 03	Ring-shaped contact lens applicator. Threshold of 0.15 mA	Authors' estimate of induced E field	**110**
Carstensen 85	Cup-shaped applicator. 25 Hz threshold of 0.04 mA	Estimate 1: From voltage drop based on homogeneous model.	**160**
"	As above	Estimate 2: Use thickness and conductivity of tissue layers within eye.	**430**
"	As above, but note the current is applied via a 25 mm diameter eye-cup	Estimate 3: Assume the cup is hemispherical	**80**
"	Estimated threshold J = 0.3 A/m^2	Estimate 4: Threshold J based on model of Lindenblatt & Silny.	**600**
Lovsund 80a	Threshold 0.08 mA applied between temples	Assume half of this goes through the eyeball, with a constant current density	**80**
Adrian 77	0.01- 0.02 mA threshold.	Applied over bony edge of orbit to just in front of contralateral ear. Current spread out over an area of face or restricted to eyeball?	**1.3 - 38**
Knighton 75a	Frog retina, **DC** current thresholds range 0.005 - 0.044 mA	Threshold for DC E-field 600 – 30,000 mV/m depending on value of σ chosen (see text).	**-**
Knighton 75b	Microelectrode work: measures tissue voltage in situ in response to 1 μA **DC** current.	Slope of voltage vs. distance gives 2.4 V/m gradient on scleral side of retinal tissue. Converting current to current density implies σ = 0.01 S/m.	**-**
Brindley 56a	Microelectrode work on frog eye	**DC** currents: note data on retinal resistance implies σ = 0.01 S/m	**-**
Brindley 55	Threshold: 0.017 mA at **50 Hz** across human conjunctiva	Phosphenes sensed in region of retina (over a 17 mm^2 area) immediately below applicator. J thus around 1 A/m^2	**100 - 400**

Magneto-phosphenes: 20 Hz Thresholds

Author(s)	Basic finding @ 20 Hz uos	Assumptions made: direction of induced current	mV/m
Taki 03	Threshold of 5 mT in humans	Author's estimate, using modelling: Circumferential	**4 - 16**
Lovsund & Nilsson 81	Threshold of 20 mT for isolated frog retina	5 mV/m assuming a 4 mm radius of the excised retina: Circumferential	**5**
Lovsund 80b	Threshold of 10 mT average B field value within eyeballs in humans	Estimate 1: Assuming r = 13 mm i.e. radius of eyeball (isolated sphere model): Circumferential.	**8**
"	As above	Estimate 2: Assuming r = 70 mm (distance of retina from centre of skull): Radial to eyeball	**44**
"	As above	Estimate 3: As above, but local areas of greater current density (blood vessels through sclera Lindenblatt & Silny 2002): Radial	**100**

20 Hz Thresholds with 95% Conf. Intervals

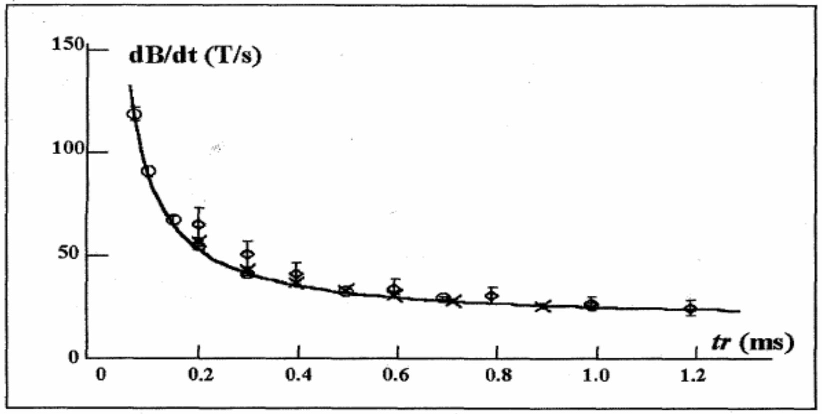


Pooled estimate for phosphenes

- Assume both phenomena are equivalent
- Pooled: mean 56 (2.3 – 1330 85%CI) mV/m
- Close to IEEE value of 53 mV/m, but in view of large range, ARPANSA chose 'power of 10', i.e. 100 mV/m
- At 50 Hz this is 250 mV/m
- Since retinal tissue thought to be the most sensitive, compliance to be evaluated in *this* tissue (not brain in general)

Peripheral Nerve Stimulation

- Can occur in patients undergoing MRI if magnetic field gradients switched too rapidly
- a) Nyenhuis et al. (2001) and b) Chronik & Rutt (2001) estimate median sensation threshold (rheobase) of 1.3 – 2.1 V/m from experimental & modelling studies with human volunteers
- For f < 3 kHz, sensation threshold ~ 18.8 T/s



Data from den Boer et al. J Mag Res Imag 15:520 (2002)

Peripheral Nerve Stimulation

- Assume threshold E independent of frequency below 3kHz (dB/dt is flat and $\propto$ E)
- Population in a) of 84 had range of ±50% and margin of ~ 2 between sensation and intolerable pain.
- Justifies relating limit to median for **sensation i.e. 2 V/m** (c.f. 6.15 V/m in IEEE)

From Nyenhuis et al. CRC Press

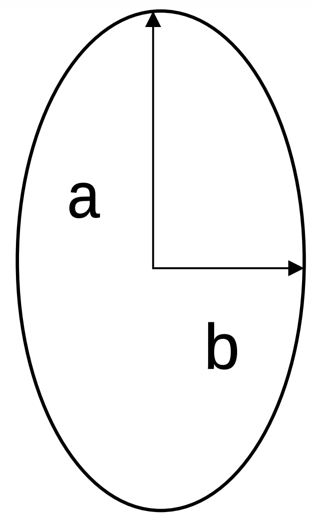
Margins for safety

- Because of uncertainties, margin of 10 between effect threshold and occupational Basic Restriction favoured
- Further margin of 5 to get BR for General Public: consistent with range of sensitivities in general population (factors such as gender, size, epilepsy etc.)
- Follows ICNIRP, but not IEEE (which has margins of 3 + 3)

Derivation of Reference Levels

- IEEE: Prolate spheroid model of torso, limbs
  - a & b are specified for different regions
  - For sphere, get familiar E = - (dB/dt).½.r
  - From Basic Restriction values for E, the corresponding dB/dt can be derived and hence B, since for sinusoids dB/dt = 2πf.B

$$E = -\dot{B}_w \left| \frac{a^2 u a_v - b^2 v a_u}{a^2 + b^2} \right|$$



Formula from ICES, Annex B

Derivation of Reference Levels (2)

- Use anthropomorphic models: e.g. NORMAN (♂) & NAOMI (♀)
  - 2 mm resolution
  - internal J and E for external magnetic & electric fields mapped
  - Uses characteristic conductivity values for > 30 tissue types
  - Anatomical details derived from MRI & CT information
  - For each tissue type, average, maximum and 99 percentile values calculated

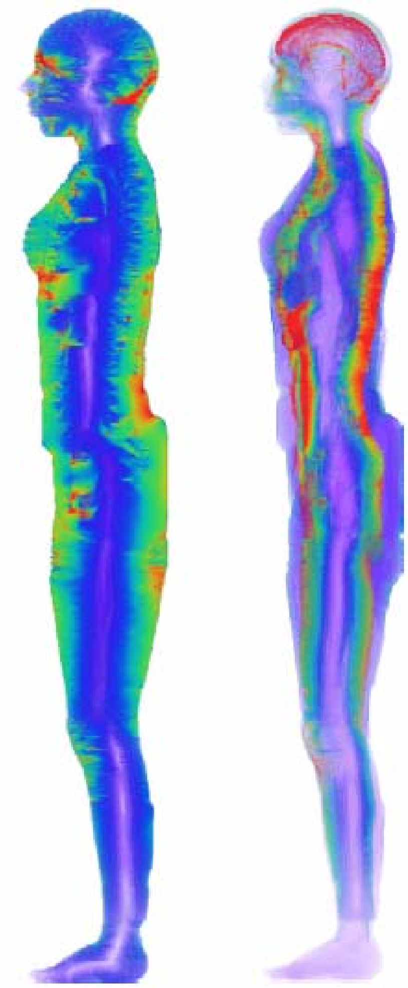


Diagram from Dimbylow 2005 E_{int} J_{int}

Derivation of Reference Levels

- Magnetic field: from voxel models e.g. Dimbylow 2005
  - Retina 99%ile value: 14.6 mV/m per mT (50 Hz)
  - Tissue associated with PNS: 3 V/m per mT (3 kHz)
- General Public Basic Restriction exceeded as follows:
  - Retinal BR value (5 mV/m) exceeded at 0.3 mT (50 Hz)
  - PNS BR value (40 mV/m) exceeded at 0.012 mT (3 kHz)

Derivation of Reference Levels (2)

- Electric field: from voxel models e.g. Dimbylow 2005
  - Retina 99%ile value: 0.55 mV/m per kV/m (50 Hz)
  - Tissue associated with PNS: 0.18 V/m per kV/m (3 kHz)
- General Public Basic Restriction exceeded as follows:
  - Retinal BR value (5 mV/m) exceeded at 9.1 kV/m (50 Hz) (round this to 10 kV/m)
  - PNS BR value (40 mV/m) exceeded at 0.22 kV/m (3 kHz)

Derivation of Reference Levels (3)

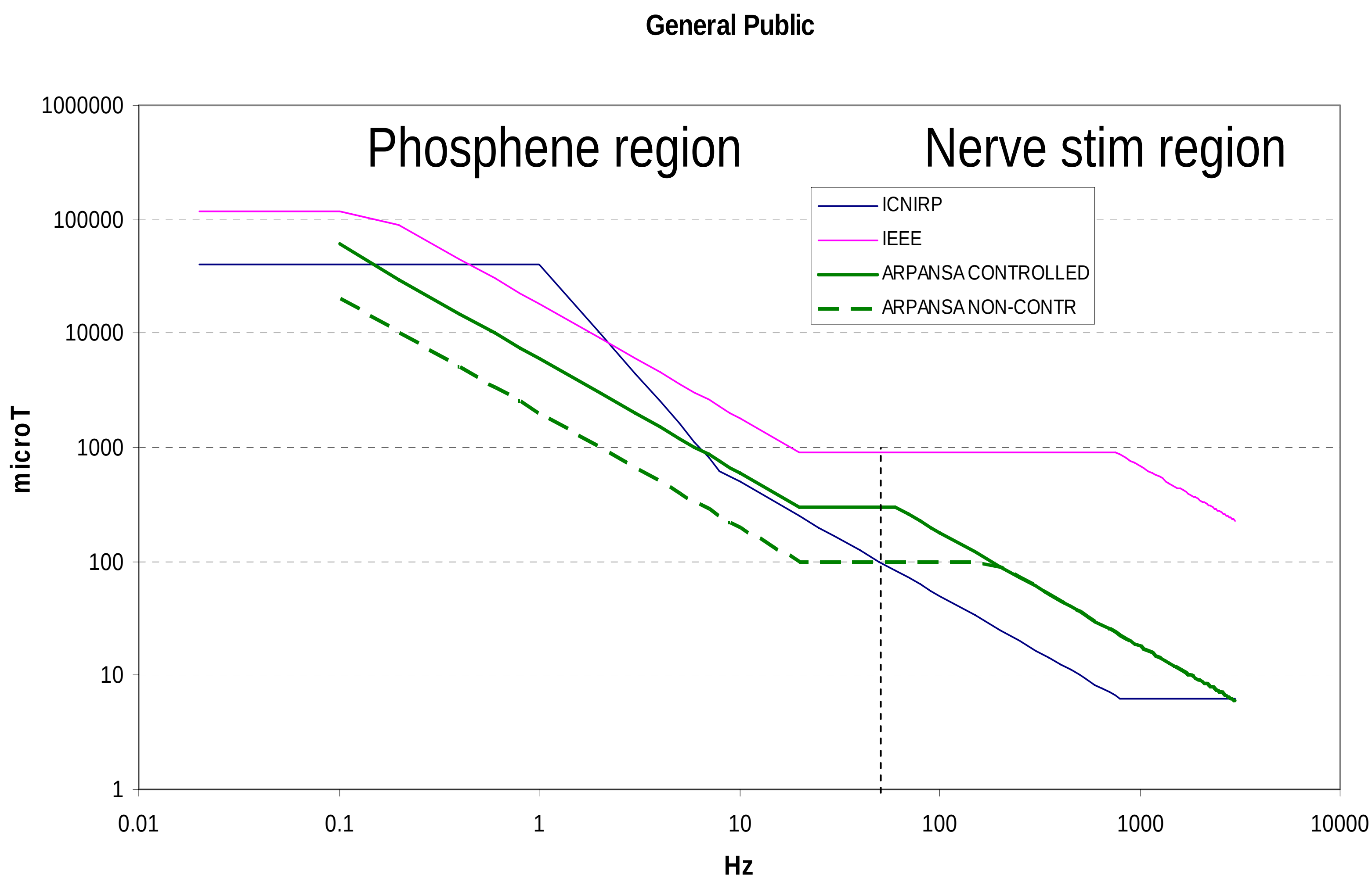
- Some uncertainty, so:
  - Use these figures to determine limits for 'Controlled Activity/Circumstance'
  - 'Regular' limits are similar to ICNIRP for electric fields, but in the case of magnetic fields are similar at 50 Hz, but follow the IEEE 'shape'
  - 'Controlled Activity/Circumstance' proposed for both Occupational and General Public groups: emphasis on a) exposure minimisation and b) warning

Occupational Levels

- Magnetic fields
  - 5 x General Public limits for both 'Controlled Activity' and 'Regular' limits
  - Where exposure to head not involved, nerve stim. considerations apply for entire range
- Electric fields
  - 5 x General Public limits for 'direct effects'; 2 x General Public limits for 'indirect effects'

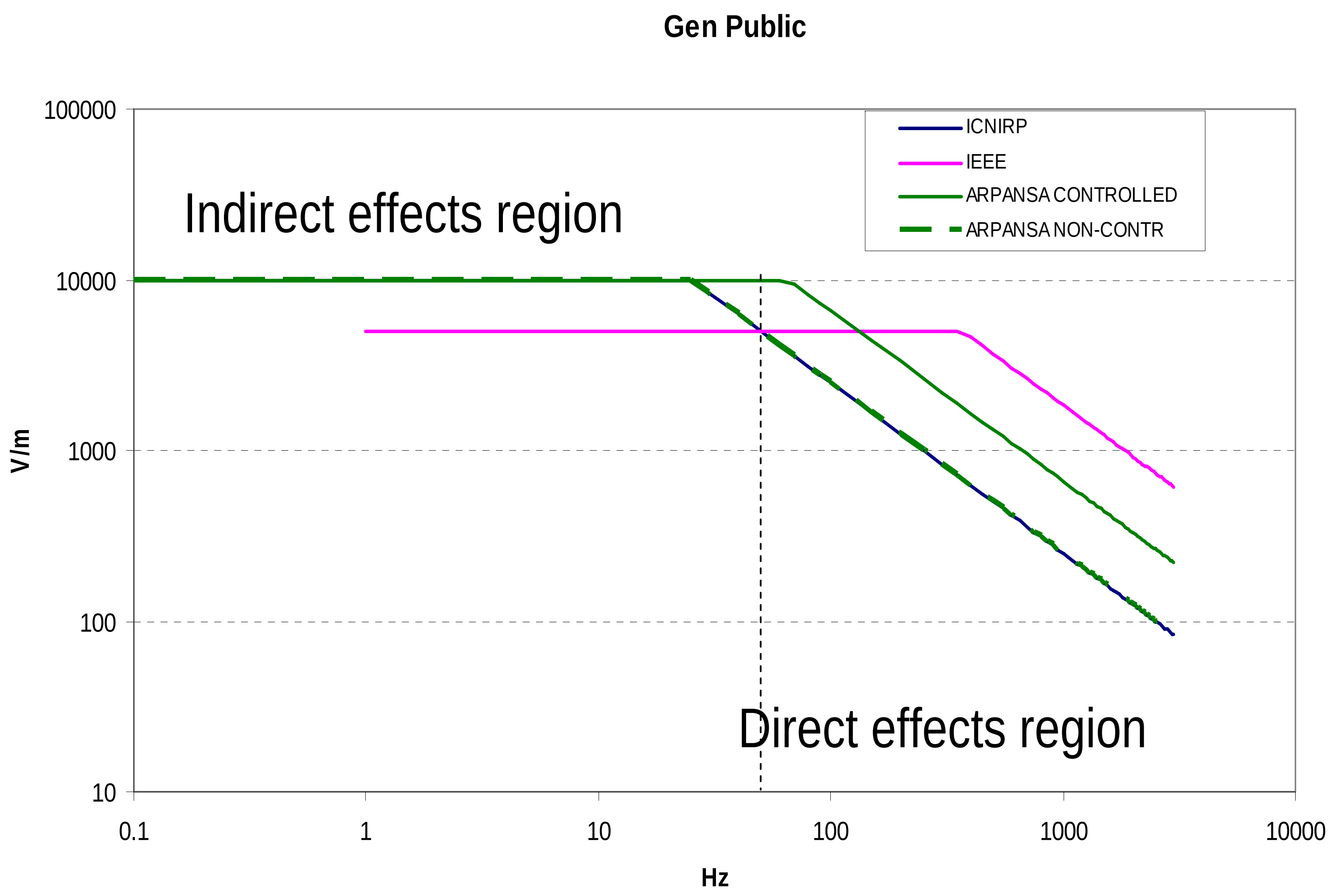
Reference Levels (General Public)

- Magnetic Fields



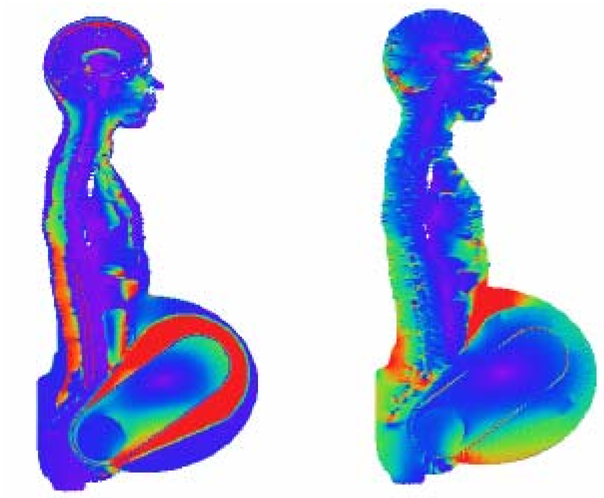
Reference Levels (General Public)

- Electric Fields



Derivation of Reference Levels (3)

- Latest HPA modelling data includes pregnant female
  - ☐ 99th percentile values: max in foetus of around 30 mV/m for 1 mT external magnetic
  - ☐ Corresponding 1.7 mV/m for 1 kV/m external electric
  - ☐ For 10 kV/m this is 17 mV/m in foetal brain: value in retina uncertain at this stage



J_{int} E_{int}

Diag. from Dimbylow 2006

But what about leukaemia?

- Epidemiological Evidence
  - Annex discusses this, especially post IARC
  - As with IEEE, ICNIRP, WHO the draft does not consider the evidence strong enough to be considered causal, thus it doesn't form basis for limits
  - Justifies Precautionary Approach
- Low level exposures
  - Evidence from animal and laboratory studies post-2000 are also reviewed in an annex, especially in relation to the cancer issue
  - Little has emerged to resolve uncertainty

Precaution: Clause 5.7e (emphasis added)

Measures for the protection of members of the **general public** who may be exposed to ELF and/or static fields due to their proximity to high ELF and/or static sources **must** include the following:

…………..

e) Minimising, as appropriate, ELF and/or static electric and magnetic field exposure **provided this can be readily achieved without undue inconvenience and at reasonable expense.** Any such precautionary measures should follow good engineering and risk minimisation practice. Planning practice and relevant codes of practice should also be followed. Precautionary measures should be proportional to the risk. (i.e where children are involved). Important principles underlying appropriate precautionary measures are discussed in Annex 6. The incorporation of arbitrary additional safety factors beyond the exposure limits of this Standard is not supported.

Precaution: Clause 5.7e (emphasis added)

Measures for general public

must include

e) Minimising electric and magnetic field exposure **provided this can be readily achieved without undue inconvenience and at reasonable expense.**

appropriate precautionary measures are discussed in Annex 6.

Annex 6: possible precautionary approaches

Research	■Reduce uncertainty ■Better characterize fields near sources
Communication	■Give information to allow individuals to reduce personal exposure
Engineering	■Enforce wiring practices to reduce fields ■Reduce ground currents in distribn. systems ■Changes in transmission line and appliance design
Planning	■Minimise exposure from overhead HV wiring via changes in planning procedures
Exposure limits	■Precaution is about reducing exposure, not setting arbitrarily lower limits

Office of Regulatory Review process

- Regulatory Impact Statement has to be cleared by them: Options
  - ☐ Do nothing (keep 50 Hz ICNIRP figures)
  - ☐ Regulatory adoption
  - ☐ Publish Standard without regulation: education strategies for leukaemia issue (Precautionary Approach)
- Cost-Benefit Analysis performed:
  - ☐ Costs: Industry compliance & governmt. admin.
  - ☐ Benefits: 'Willingness to pay' to avoid possibility of some lives lost AND/OR less than perfect health

Summary: state of play

- Basic restrictions based on
  - Retinal phosphene data from humans and animal studies
  - Peripheral nerve stimulation data: human volunteer studies from magnetostimulation in MRI
- Reference Levels based on
  - Latest voxel-based modelling data
  - Direct effect for both B and E fields, except for low frequency part of E-field limits

Summary: state of play (2)

- Regulatory Impact Statement
  - Modest benefit from non-regulatory option
  - Educational material on leukaemia issue for ARPANSA website being developed
- Public Comment Draft (Standard + RIS) release
  - Before start of December: 3 month comment period
  - Copies to be provided to Working and Consultative groups and State/Territory regulators prior to release – for information & checking
  - ARPANSA website to provide some guidance on measures to reduce exposure + Q & A section

What to expect on ARPANSA website?

1. Draft Standard
2. Draft Regulatory Impact Statement
3. Advisory material on childhood leukaemia risk in relation to Standard
4. Advice on reducing exposure to fields
5. Question & Answer section
6. Press release

Need now: List of emails of those wishing to be notified of date of release of material

Where to look? www.arpansa.gov.au/for_comm.htm

Controlled Activity or Controlled Circumstance (Occupational Exposure)

An activity or circumstance in which exposure to ELF electric or magnetic fields may reasonably be expected to exceed occupational exposure reference levels as given in Tables 3 & 4 but not to exceed the Controlled Activity/Circumstance (Occupational Exposure) reference levels of Table 3 & 4.

Such exposure is permissible only if the persons being exposed:

- are made aware of the probable exposure and given information about possible biological effects and risk of adverse health effects;
- give informed consent to such exposures;
- are given sufficient training and information so they may minimise their exposure consistent with operational requirements and may avoid accidents or injuries if biological effects do occur; and
- are suitably screened for the presence of electronic or metallic medical implants that may put them at risk in the range of fields expected.

Such activity or circumstance must also be:

- under the supervision of a competent person who must ensure that exposures cannot exceed the Controlled Activity/Circumstance (Occupational Exposure) reference levels;
- be subject to appropriate access controls and signage to prevent inadvertent entry and exposure; and
- be documented and signed so that areas exceeding normal occupational reference levels are clearly indicated.

Where a Controlled Activity or Controlled Circumstance is likely to result in exposures exceeding the normal occupational reference levels for more than one hour per day, records of staff undertaking the activity must be kept giving estimated weekly exposure times and levels.

Controlled Activity or Controlled Circumstance (Public Exposure) (including Aware user exposures)

An activity or circumstance in which exposure to ELF electric or magnetic fields may reasonably be expected to exceed public exposure reference levels as given in Tables 3 & 4 but not to exceed the Controlled Activity/Circumstance (Public Exposure) reference levels of Tables 3 & 4.

Such exposure is permissible only if:

- signage at all entry points is present to inform all likely visitors/occupants that the fields exceeding the general public limits may be present and that visitors/occupants may wish to minimise the duration of their stay;
- that such signage includes reference by telephone number (available at least during normal business hours) and internet URL to a source of more comprehensive information about the likely exposure levels, and possible risks to health;
- that where exposures are highly localised, the signage clearly indicates which locations are effected; and
- documentation is prepared and maintained explaining why such exposures are practically necessary.

TABLE 3

REFERENCE LEVELS FOR EXPOSURE TO RMS MAGNETIC FIELDS

Exposure category	**Frequency range**	**B-field strength (μT rms)**	**"Controlled Activity" B-field strength (μT rms)**	**"Controlled activity" Exposure to regions other than head B-field strength (μT rms)**
Occupational	0.1 – 20 Hz	$10^4/f$	$3 \times 10^4 / f$	$9 \times 10^4/f$*
	20 – 60 Hz	500	1,500	$9 \times 10^4/f$
	60 –180 Hz	500	$9 \times 10^4/f$	$9 \times 10^4/f$
	180 – 3,000 Hz	$9 \times 10^4/f$	$9 \times 10^4/f$	$9 \times 10^4/f$
	50 Hz	500	1,500	1,800
General public	0.1 – 20 Hz	$2 \times 10^3/f$	$6 \times 10^3/f$	N/A
	20 – 60 Hz	100	300	N/A
	60 – 180 Hz	100	$1.8 \times 10^4/f$	N/A
	180- 3,000Hz	$1.8 \times 10^4/f$	$1.8 \times 10^4/f$	N/A
	50 Hz	100	300	N/A

NOTES:

1 ***f* is the frequency in Hz**.

**** To a maximum of 200,000** μT rms*

TABLE 4

REFERENCE LEVELS FOR EXPOSURE TO RMS ELECTRIC FIELDS (UNPERTURBED FIELDS)

Exposure category	Frequency range	E field strength (V/m rms)	Controlled Activity E field strength (V/m rms)
Occupational	0.1 – 25 Hz	20,000	20,000
	25 – 165 Hz	$5 \times 10^5/f$	20,000
	165 – 825 Hz	$5 \times 10^5/f$	$3.3 \times 10^6/f$
	820 – 3,000 Hz	614	$3.3 \times 10^6/f$
	50 Hz	10,000	20,000
General Public	0.1 – 25 Hz	10,000	10,000
	25 – 66 Hz	$2.5 \times 10^5/f$	10,000
	66 – 3,000 Hz	$2.5 \times 10^5/f$	$6.6 \times 10^5/f$
	50 Hz	5,000	10,000

NOTES:

***f* is the frequency in Hz**.

WORKING GROUP

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