Ensuring Effective Protection against ELF Adverse Effects: The Australian Experience

A.W. Wood¹,²,³

¹ Swinburne University of Technology, Melbourne, Australia
² Australian Centre of RF Bioeffects Research, Melbourne, Australia
³ Chair, ELF Working Group, Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), Melbourne, Australia

Abstract — A recent Environmental Health Criteria (EHC) monograph on Extremely Low Frequency fields (ELF) involved health risk assessment [1]. It recommended that exposure limits were needed to protect against certain established acute effects which could lead to adverse health. It noted the evidence for long-term low-intensity exposure being associated with increased risk of childhood leukaemia for average time-weighted exposure above 0.3 – 0.4 μT, but considered that the evidence was insufficiently strong to be considered causal. However, because of this evidence, procedures for implementing very low-cost precautionary procedures for reducing exposure were considered to be warranted.

The Australian radiation protection agency, ARPANSA, commenced revision of 50/60 Hz guidelines, to encompass the 0 – 3 kHz frequency range, in 2002. The drafting committee considered local and international expert input as well as from stakeholders. The rationale behind the public consultation draft is reviewed in this paper. To protect against established effects, Basic Restrictions were derived by reassessing the literature, including the more recent data from MRI studies. Reference Levels were then derived making use of recent voxel-based models of male & female humans.

A requirement for considering low-cost precautionary measures was included, with an annex discussing the form that these measures could take.

Keywords — Extremely Low Frequency, Standards, Precaution.

I. INTRODUCTION

The question of protection against putative hazards of Extremely Low frequency (ELF) Electric and Magnetic Fields (EMF) is controversial. For many years the basis for ELF restriction was the prevention of microshocks arising from the coupling of electric fields (E-fields) to the body, mainly potentially experienced by workers in the electrical power industry. The 1979 epidemiological study of Wertheimer & Leeper [2] shifted concern to magnetic fields (B-fields) and to long-term exposure in the home. The issue of childhood leukaemia is an emotive one and thus the public perception of risk has been a driver when national and international bodies have sought to produce advice or regulation for their jurisdictions or member organizations.

Australia was one of the first nations to adopt power frequency guidelines when it adopted the recommendations of ICNIRP (then IRPA) in 1989. A revised radiofrequency (RF) standard (also based on ICNIRP) was adopted in 2002, but the lowest frequency covered was 3 kHz. Australia (via the Australian Radiation Protection and Nuclear Safety Agency, ARPANSA) has been developing a standard for the frequency range 0 – 3 kHz, and this was released for public comment at the end of 2006. This paper briefly summarises some of the issues the working group considered in producing this consultation draft.

II. POSSIBLE ADVERSE EFFECTS

A. Short-term and long-term effects

As the amplitude of electric or magnetic field is progressively increased there comes a point where these fields are sensed and then a further point at which these sensations become hazardous. These effects relating to sensation occur within seconds of exposure and cease once the exposure stops. In contrast to dangers of electric shock from contact with electrical conductors, it is very rare for EMFs to be sufficiently high to give rise to sensations, except in certain electrical occupations (such as live-line maintenance work), but here work practices are such as to minimise if not eliminate their occurrence. These sensations arise from stimulations of the nervous system and there comes a point where they cease being mildly annoying and begin to be a major distraction or worse, lead to a reflex withdrawal of a limb with consequent loss of balance and injury.

As opposed to these, almost trivial risks, the possibility of increased incidence of childhood cancer is severe, even though in terms of numbers the likely impact is small. Since the original Wertheimer & Leeper study there have well over 100 epidemiological studies involving EMF, with several tens examining child leukaemia. Although causality has not been established, the association cannot be attributed to chance. If the link were causal, a risk estimate is of around 2 - 6% of cases of a fortunately rare disease [de Klerk: this volume].
B. The phosphene

This phenomenon of ‘seeing stars’ can occur when the eyeball is rubbed or poked – in this case it is a pressure phosphene. Similar sensations can be elicited when eyeball is stimulated by electrical current. It seems to originate within retinal tissue rather than optic nerve. Since the retina is designed to detect light these other stimuli are termed ‘inadequate stimuli’ because they lead to an abnormal response. It is therefore reasonable to try to prevent this from occurring. There is also a concern that effects with more severe consequences may be occurring elsewhere in the Central Nervous System (on memory processes for example) but without the obvious sensory manifestations. However, there are a number of reasons why the retinal phosphene may be the most sensitive indicator of ELF effects. Retinal architecture is quite unique in its close packing of cells, high connectivity, little myelination, graded responses, electrical synapses and specialized ‘Ribbon synapses’. Both magneto- and electro-phosphenes have been studied in human volunteer and in-vitro experiments with excised animal tissue. By comparing the available literature and making certain assumptions it is possible to estimate the tissue electric field threshold for these phenomena. At the most sensitive frequency, 20 Hz, the pooled mean threshold (with 95% CI) is 56 (2.3 – 1330) mV/m.

In view of this large range, ARPANSA chose a ‘power of 10’, (i.e. 100 mV/m) as the basis of restrictions. This also happens to be close to the IEEE value of 53 mV/m. Since above 20 Hz this threshold can be assumed to vary as f/20 (f in Hz), the 50 Hz value is 250 mV/m.

As discussed, since retinal tissue thought to be the most sensitive, compliance is to be evaluated in retinal tissue (not brain in general).

C. Peripheral Nerve Stimulation

This can occur in patients undergoing MRI if magnetic field gradients switched too rapidly, causing sensations in regions of the body or twitches. There are various estimates in the literature from human volunteer experiments, together with mathematical modelling. For example, [3, 4] estimate median sensation threshold (rheobase) of 1.3 – 2.1 V/m fields within tissues. In terms of time rate of change of B-field (dB/dt), the sensation threshold has been measured to be 18.8 T/s, for sinusoidal fields below 3 kHz. Since the induced field \( E_{int} \) is proportional to \( dB/dt \), it can be assumed that this quantity is also constant below approximately 3 kHz.

Since the study population (n = 84) in [3] had a range of ±50% in threshold and since a margin of around 2 between sensation and intolerable pain was reported, ARPANSA felt justified in relating the limit to the median for sensation i.e. 2 V/m (compared with 6.15 V/m in IEEE) at all frequencies below 3 kHz.

III. SAFETY MARGINS

Because of uncertainties in estimates, a margin of 10 between effect threshold and occupational Basic Restriction (BR) is favoured by ARPANSA, with a further margin of 5 to get BR for General Public. The latter is consistent with the range of sensitivities in the general population due to factors such as gender, body size, disease status (such as epilepsy etc.).

This follows the safety margins set by ICNIRP, but not by IEEE, which has margins of 3 both between effect threshold and occupational levels and between the latter and general public levels (although the precise margin varies with the tissue concerned).

IV. REFERENCE LEVELS

A. General Approach

Since BRs refer to internal tissue quantities they are difficult to measure to demonstrate compliance. It is important to estimate the values of external fields which would give rise to these BRs: the field values are known as Reference Levels (RLs). Estimating these RLs can be done a number of ways, by using: i) simple geometric representations of human body; ii) electrolyte-filled phantoms; iii) (animal) cadavers or iv) realistic voxel-based models of the human with correct organ electric properties. The first has been used for ICNIRP and IEEE, but the fourth has been used by ARPANSA. Anthropomorphic models such as NORMAN (♀) and NAOMI (♀)[5], which have 2 mm resolution, characteristic conductivity values for > 30 tissue types and anatomical details derived from MRI & CT information permit the estimation of induced current density \( J \) and \( E_{int} \) in each voxel. For each tissue type, average, maximum and 99 percentile values are calculated.

B. Magnetic field RLs

From table 6 of [5] the highest estimate of 50 Hz induced electric field in retinal tissue (99%ile value) is 14.6 mV/m per mT (for normal conductivity values). From this, the Retinal General Public BR value of 5 mV/m would be exceeded at just over 0.3 mT (50 Hz). For convenience, in the ARPANSA draft this was rounded to 0.3 mT. Since the external field required to induce a particular \( E_{int} \) value varies with 1/f and the BR itself rises with f above 20 Hz, these two frequency effects cancel and the value 0.3 mT applies for all frequencies above 20 Hz up to frequencies at which PNS effects become more of a concern. Below 20 Hz, the RL for the General Public is given by the formula \( B = 6/f \) mT (f in Hz).

For tissue associated with PNS activation, some interpolation of data is required: at 50 Hz the largest \( E_{int} \)
induced in excitable tissue in [5] is around 50 mV/m per mT (bladder). Caputa et al. [6] give a rather higher value of 70 – 90 mV/m per mT at 60 Hz. Since 3 kHz is a more appropriate frequency to be considering PNS, 90 mV/m would correspond to 4.5 V/m per mT at this higher frequency. The ARPANSA working group considered that there were configurations where this $E_{\text{int}}$ could be higher, so the value was increased to 6 V/m per mT (3 kHz). The 40 mV/m General Public Basic Restriction would thus be exceeded as follows: 0.006 mT (3 kHz, rounded down) and at other frequencies $B = 18/f$ (mT).

The corresponding Occupational RLs are five times those given above. There is a transition point at 60 Hz from the RLs being determined by the prevention of phosphenes to the prevention of PNS effects.

C. Electric field RLs

Following the procedure in B above, the retinal 99%ile value in [5] is given as 0.55 mV/m per kHz (50 Hz). Thus the General Public Retinal BR value of 5 mV/m would be exceeded at 9.1 kV/m at frequencies from 20 Hz to those at which PNS becomes more of a concern. The working Group decided, for simplicity, to round this to 10 kV/m. However, since indirect effects (micro-shocks) can occur in uncontrolled environments below this, a RL of 5 kV/m applies, unless certain extra precautionary measures are in place.

From table 9 in [5] the more conservative figure for 99%ile value for 0.55 mV/m per kHz (50 Hz). Thus the General Public Retinal BR value of 5 mV/m would be exceeded at 9.1 kV/m at frequencies from 20 Hz to those at which PNS becomes more of a concern. The working Group decided, for simplicity, to round this to 10 kV/m. However, since indirect effects (micro-shocks) can occur in uncontrolled environments below this, a RL of 5 kV/m applies, unless certain extra precautionary measures are in place.

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For Occupational exposures, the RLs are five times the values given above, except below the transition frequencies (in this case 165 Hz for controlled and 330 Hz for uncontrolled circumstances) where the difference is only two times. This recognises the lower margins between sensation and pain for microshocks.

V. PRECAUTIONARY APPROACHES

The RLs for the General Public at 50 Hz are thus 0.3 mT and 5 kV/m (uncontrolled) for B-fields and E-fields respectively. These are intended to be measured over a short averaging time of less than a second (normally 0.1 sec: in the draft, a longer averaging time of 5 sec is intended only for rare ‘spikes’). Epidemiological studies, in which there is only evidence of an association with B-fields and not E-fields, use metrics which assess long-term exposure, often in the form of a ‘time-weighted average’ (TWA) over a period of 24 hours or longer. Residential TWA exposures usually have median values around $10^4$ mT (0.1 μT). Only a few percent of values exceed 0.3 or 0.4 μT, but it is these unusually high values for homes that the evidence is based. IEEE, ICNIRP and WHO do not consider the evidence strong enough to be considered causal, thus it does not form basis for limits. It does (in the working group’s view, at least) justify a ‘Precautionary Approach’. There is also the question of the large number of laboratory experiments, with exposures below the RL limits just discussed, which are often taken to indicate harm. These animal and laboratory studies have been reviewed many times, especially in relation to the cancer issue, but results have been inconsistent. However, long-term in-vivo experiments are almost all negative and there is no convincing biophysical mechanism linking low-level exposures to disease. Currently no adequate explanation of increased leukaemia risk exists, and the connection with B-fields may be indirect. The aim in a precautionary approach is to reduce leukaemia risk, even if EMF not causal. The general philosophy is to avoid unnecessary exposure by recommending good work practices or by design or other criteria which, at no or low cost, reduce exposure.

The draft ARPANSA standard espouses the use of precaution in Occupational Exposures as well as of the general public. Specifically, measures for general public must include: “Minimising…. electric and magnetic field exposure provided this can be readily achieved without undue inconvenience and at reasonable expense” and signage to enable personal precautionary strategies in areas where fields are unusually high and long-term exposure likely.

Appropriate precautionary measures are discussed in an Annex of the draft following the approaches in Table 1.

Table 1 Possible precautionary approaches

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<thead>
<tr>
<th>Options</th>
<th>Outcomes</th>
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<tr>
<td>Research</td>
<td>Reduce uncertainty</td>
</tr>
<tr>
<td>Communication</td>
<td>Better characterize fields near sources</td>
</tr>
<tr>
<td>Engineering</td>
<td>Enforce wiring practices to reduce fields</td>
</tr>
<tr>
<td>Planning</td>
<td>Minimise exposure from overhead HV wiring via changes in planning procedures</td>
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<tr>
<td>Exposure limits</td>
<td>Precaution is about reducing exposure, not setting arbitrarily lower limits</td>
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VI. REGULATORY IMPACT

In Australia, introducing a standard has resource implications. This is true, even for a standard which is not incorporated into legislation. ARPANSA Radiation Protection Series publications are accompanied by Regulatory Impact Statements (RIS) where applicable. Part of the RIS is an economic Cost-Benefit Analysis (CBA). This examines both industry compliance & government administration costs and identified benefits, such as ‘willingness to pay’ to avoid possibility of some lives lost and/or less than perfect health. The draft RIS identified a modest benefit from non-regulatory option (AUD4M). This option is coupled with the provision of educational material on leukaemia issue for ARPANSA website. The draft Standard together with RIS was available for public comment during the period Dec 2006 – end Feb 2007 with 64 submissions received. A revised draft, incorporating comments where appropriate, is expected to be available by the end of 2007. Predictably, submissions ranged from questioning its conservatism, given that many occupations had involved high field exposure for decades without clear evidence of harm, and on the other side community groups arguing for the need of a limit below 0.4 μT, to prevent leukaemia. MRI users argued that the ICNIRP-based limits for static fields were unrealistic.

VII. SUMMARY AND CONCLUSIONS

ARPANSA’s ELF working group has developed a limits-based standard for short-term neurostimulatory effects, with 10/50 safety margins for occupational and general public groups respectively. It also incorporates a mandatory Precautionary Approach based on: exposure minimisation via low-cost or no cost means (including building design regulations). This also espouses advisory signs of ‘unusually high’ field locations and the production of education material on the ‘leukaemia issue’. This precaution is for both Occupational and General Public groups.

But is this effective protection? It is assumed that ‘factor X’ (which is what causes raised leukaemia rate) will be lowered by the precautionary measures just listed. It is unclear how a non-regulated standard ensure protection and how is precaution is to be enforced. It is also possible that a non-regulated standard will acquire the same status as a regulated standard with stakeholders’ ‘duty of care’.

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The author chairs the ARPANSA ELF Standard Working Group. The views presented are personal to the author and should not be taken as representing those of ARPANSA or of the Australian Government.

REFERENCES


Address of the corresponding author:

Author: Andrew Wood
Institute: Swinburne University of Technology
Street: John St
City: Hawthorn, Vic 3122
Country: Australia
Email: awood@swin.edu.au