Human auditory perception resulting from exposure to high power pulsed or modulated microwave radiation — specification of appropriate safety limits

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Introduction

This paper gives a brief outline of the human auditory perception associated with exposure to high power short pulse radiofrequency electromagnetic fields and in particular, with the appropriate formulation and specification of human exposure limits.

Finally, a proposed revised formulation of relevant restrictions is presented as a solution to the problem. The proposed formulation introduces a new limiting quantity and alters the way in which localised pulse or modulated RF exposure to the head would be evaluated.

Auditory effect

As discussed in the rationale of the ARPANSA draft Radiation Protection Standard [7], nuisance auditory effects (Lin 1978, Lin 1990, Heynick & Polson 1996) [3,4,6] are associated with exposure to extremely high peak power short pulse systems such as high power military radar transmitters. Depending on the pulse duration, repetition rate and the rate of localised energy absorption, exposure to high power pulsed microwave radiation can produce rapid thermoelastic expansion of soft tissue within the head. The resultant acoustic pressure wave may be perceived as an audible noise that is typically perceived as a buzzing or clicking noise. The character of the sound depends on the transmitter's pulse duration, repetition rate and the amount and distribution of energy absorbed in the head. Such auditory response is produced primarily by the energy delivered within approximately the first 50 microseconds of the leading edge of each successive microwave pulse. Where the ambient noise level is low, the minimum energy to produce a perceptible auditory effect is quite small. As indicated by Lin in his paper dealing with the mechanics of the microwave auditory effect [2], although a high rate of instantaneous energy absorption is required to produce an auditory effect the localised temperature rise obtained from a single pulse can be substantially below 0.0001 ºC.

While such auditory effects are not known to cause any direct adverse health effects, it is clear that in certain situations the onset of a sudden noise could startle or otherwise distract a person from performing a vital task so as to cause a dangerous situation. For example a worker climbing a ladder on a communications tower may be startled by the sudden onset of noise and could fall from the ladder. It is clearly important and necessary to prevent such nuisance (and possibly dangerous) auditory effects.

In order to prevent auditory effects, the International Commission on Non-ionising Radiation Protection (ICNIRP) exposure guidelines of 1998 [1] provide a basic restriction to limit the localised specific absorption (SA) in the head. However, the ICNIRP localised specific absorption (SA) pulse limits as expressed in Note 7 to Table 4 of the ICNIRP 1998 exposure guidelines [1] are technically ambiguous. Unfortunately, the ICNIRP guidelines refer to an SA limit for a "pulse" but they fail to define the meaning of the term "pulse". For example, where the ICNIPRP SA restriction is used, it is also necessary to know how long a “pulse” can be before it is no longer defined as a “pulse” (1 • s, 1 ms, 1s ?). Clearly, such ambiguity was not intended when the ICNIRP restrictions were drafted.

Further considerations

Where complex amplitude modulation waveforms or elaborate pulse train sequences exist, the lack of a definition for “pulse” further exacerbates the problem of interpreting the ICNIRP Guidelines. A “pulse” could be defined by the ratio of the magnitude of the troughs to the magnitude of the peaks within a given waveform (eg. ½ peak height, or similar fraction). However, such definitions can lead to confusion where complex waveforms are involved (as in figure Y). For example, in situations where:

- peaks and troughs are relatively closely spaced;
- the amplitude difference is close to the relevant peak/height ratio used to determine the existence of a “pulse”;
- a pulse rises out of a noisy signal floor.

For such reason, among others discussed below, the reworked formulation of the SA basic restriction as defined in the draft ARPANSA Standard [7] avoids technical dependence on the definition of “pulse”.

The ICNIRP guidelines state; “Although little information is available on the relation between biological effects and peak values of pulsed fields, it is suggested that, for frequencies exceeding 10 MHz, S_{eq} as averaged over the pulse width should not exceed 1000 times the reference levels …”. – implying that:

- the magnitude of the SA restriction was based on the notion of limiting peak SAR to within 1000 times above the time averaged localised SAR level applicable for continuous wave exposure; and
- that the maximum possible duration for a “pulse” might be 1 millisecond.

Although it is not entirely clear why a factor of 1000 was chosen it is certainly a convenient number and seems to have been chosen primarily on this basis.

ICNIRP discussion under the heading “**Special considerations for pulsed and amplitude modulated waveforms”** states; “The microwave hearing effects have been attributed to a thermoelastic interaction in the auditory cortex of the brain, with a threshold for perception of about 100-400 $mJ \cdot m^{-2}$ for pulses of duration less than 30 µs at 2.45 GHz (corresponding to an SA of 4-16 $mJ \cdot kg^{-1}$).”, and in further discussion under “**Reference Levels**” — “For frequencies between about 0.3 GHz and several GHz, and for localised exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion, the specific absorption from pulses must be limited. In this frequency range, the threshold SA of 4-16 $mJ \cdot kg^{-1}$ for producing this effect corresponds, for 30-µs pulses, to peak SAR values of 130-520 $W \cdot kg^{-1}$ in the brain.”. In this regard, the following points are made:

- The ICNIRP 10 $mJ \cdot kg^{-1}$ restriction for occupational localised SA to the head is marginally above the minimum value within the ICNIRP stated threshold range of 4-16 $mJ \cdot kg^{-1}$ for hearing effects at 2.45 GHz.

- Auditory effects are complex and depend both on pulse shape, duration, pulse repetition rate, SAR distribution and many other factors including skull and brain geometry.

- The amplitude and distribution of SAR within the head are dependent on the carrier frequency of the electromagnetic radiation. Hence, SA distribution within the head will be different for frequencies other than 2.45 GHz.

- Data on acoustic response in humans at frequencies other than 2.45 GHz is limited [4] and frequencies other than 2.45 GHz may be significantly more efficient in producing an acoustic response.

Theoretical discussion

Physical considerations lead to the conclusion that mechanical shock waves will be induced only by energy that is deposited rapidly by the leading edge of an arbitrary SAR pulse waveform. A very sharp rise in SAR can lead to rapid heating of tissue and the production of thermoacoustic pressure waves formed by rapid thermoelastic expansion. However, if SAR should fall rapidly from a high level down to a very low level, the rapid decrease in SAR would not produce immediate cooling. This is because mechanisms available to cool tissue (eg conduction, blood flow etc) are relatively slow in comparison to the rate at which heat can be absorbed. As discussed in theory presented by Lin [2,3,4] radiation pressure and electrostrictive components are unlikely to be significant when compared to the thermoelastic pressure component of an acoustic wave. Additionally, in relation to cooling of tissue Lin [2] states; "tissue cooling is a slowly varying function of time and becomes appreciable only for times greater than milliseconds. Moreover, the times for production and propagation of stress waves are short compared with temperature equilibration.". It follows that a decrease in SAR, such as occurs in the trailing edge of a SAR pulse square waveform, will not induce significant acoustic pressures owing to the weak contraction rates associated with relatively slow cooling processes.

Literature on microwave auditory effects indicates that the energy delivered within the first 30 μs to 70 μs of a corresponding SAR pulse would be most efficient at producing acoustic pressure waves while the efficiency for pulses longer than about 50 μs depends primarily on peak SAR level.

If pulse energy is delivered to tissue sufficiently rapidly, thermoacoustic processes could become important as a mechanism for causing injury. Where energy is delivered into a minute volume of tissue, via a laser beam focused onto retina of eye, thermoacoustic injury mechanisms are associated only with pulse duration below about 10 μs [5]. Laser pulses with long duration cause injury largely through normal heating processes. Where RF is absorbed in tissue, physical characteristics ensure that RF energy is absorbed over considerably larger volumes of tissue than those associated with laser exposure. For RF absorption, owing to the larger absorbing volume, there will be additional time required for all components of the acoustic wave to arrive at any defined point in the head. With human exposure, the highest acoustic efficiency is reported for RF pulse duration in the range 30 μs to 70 μs (ie. notably greater than 10 μs and consistent with the preceding discussion).

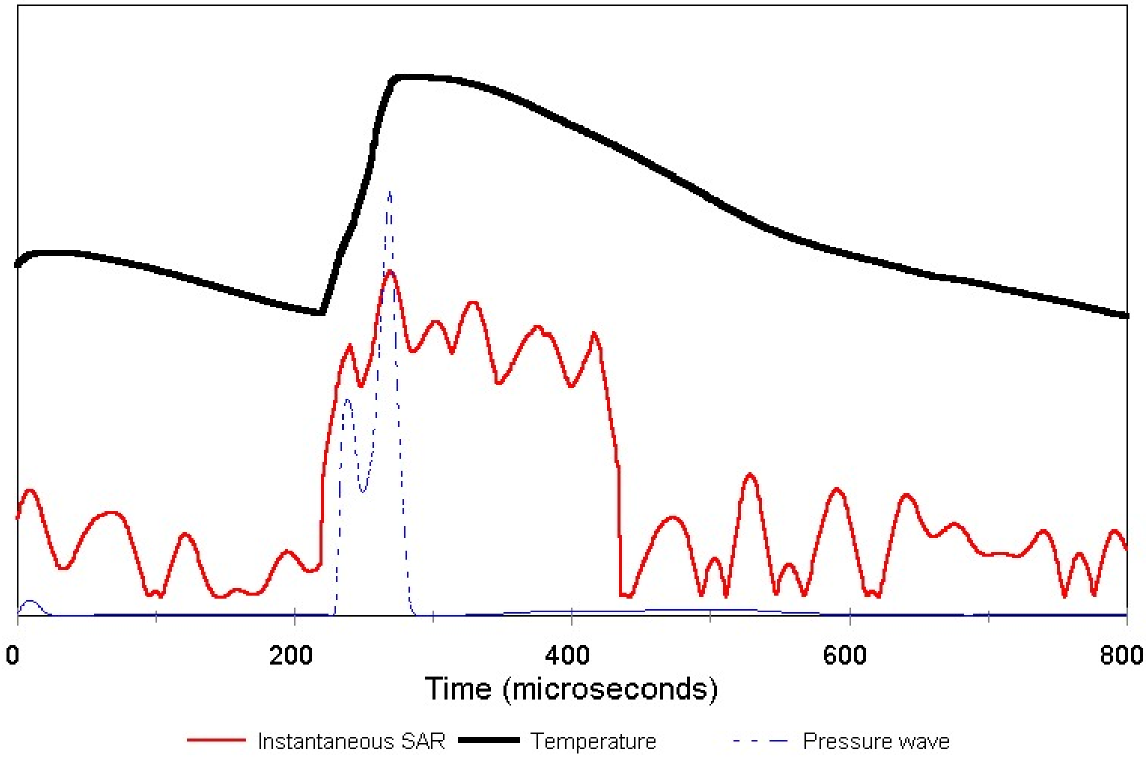

Figure 1 Simulated temperature and pressure waveforms associated with arbitrary localised SAR waveform

Figure 1 shows an arbitrary pulse waveform for localised SAR in the head where a figurative description of possible waveforms for both temperature and pressure are based on the above ideas[1].

Proposed limits

In order to prevent unwanted thermoacoustic effects, it seems necessary only to limit the energy contained within rapidly rising components (ie. leading edge) of the localised SAR waveform. However, in order to simplify the formulation of the SA basic restriction, and to allow easy determination of compliance, the draft ARPANSA Standard defines the SA restriction as being applicable to the evaluation of any 50 μs period within any SAR waveform. The magnitudes of the existing ICNIRP SA occupational and public exposure limits remain unchanged.

[1] Temperature and pressure as shown if figure 1, were crudely modelled in a spreadsheet. Temperature was based on temporal averaging/smoothing of total energy delivered over arbitrary time scales for heating and cooling effects. Pressure was based on 2nd derivative of the positive temperature gradient. This modelling also assumes that RF energy absorption occurs within a few centimetres of absorber thickness and that no acoustic wave reflections arise from boundary regions.

For very short pulses measured over an undefined “pulse” interval, the ICNIRP concept of limiting the peak SAR to a maximum of 1000 times above six-minute time averaged values is used. Both fundamental restrictions can be readily evaluated with any waveform (ie. pulsed, amplitude modulated or quasi-cw).

The re-formulation of the ICNIRP pulse restrictions as it appears in the draft ARPANSA Standard [7] is as follows:

TABLE 3

PULSED OR AMPLITUDE MODULATED EXPOSURE — BASIC RESTRICTIONS FOR SPATIAL PEAK ABSORPTION

Exposure category	Frequency range	Spatial peak SA in the head within any 50 μs interval (mJ/kg)	Instantaneous spatial peak SAR in the head and trunk (W/kg)
Occupational	10 MHz–6 GHz	10	10 000
General public	10 MHz–6 GHz	2	2 000

NOTES:

1 Spatial peak specific absorption (SA) is determined by evaluating the total energy delivered to any 10 g of contiguous tissue in the shape of a cube tissue within any 50 microsecond period.

2 Instantaneous spatial peak SAR is determined by evaluating the total energy delivered to any 10 g of contiguous tissue in the shape of a cube tissue within any 1 μs period.

Summary of technical changes

Technical points of significance regarding the reformulated limits of the ARPANSA draft Standard [7] are:

- For any given exposure, all localised SAR waveform components are subject to the new restrictions (ie. new restrictions have no dependence on the meaning of the arbitrary term “pulse”).
- The limits are unambiguous and readily amenable to analysis for compliance assessment purposes.
- Relevant “safety” margins are maintained and clearly eliminate the possibility of any adverse/unwanted effects occurring;
- There is an effective SA limit applicable to all waveform components, now evaluated within consecutive 50 μs periods.

- The peak SAR restriction is clearly specified and remains predominant for short pulse components.

- The SA limit is clearly identified as an important basic restriction (ie. no longer a footnote to a table).

- All of the basic restrictions of ICNIRP table 4 still apply.

- In addition to providing protection against the more familiar hazards of long acting thermal processes, the revised basic restrictions of the draft ARPANSA Standard serve to protect against auditory nuisance effects and other adverse effects of short transient pulses.

References

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3. Lin, J. C., **"***Microwave Auditory Effects and Applications", *C.C. Thomas, Springfield, Illinois, USA, ISBN 0-398-03704-3; 1978

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7. ARPANSA draft for public comment "*Radiation Protection Standard - Maximum Exposure Levels to radiofrequency fields — 3kHz to 300GHz*", March 2001.