

On Acceptable Exposures to Short Pulses of Electromagnetic Fields

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SEPTEMBER 2015

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FOREWORD

This document was prepared in response to a request to study the effects of exposure to short pulses of electromagnetic fields. The author is a physicist at the Naval Air Warfare Center Weapons Division (NAWCWD) Code 4F0000D; this work was funded by the Physics Division.

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Released for publication by
S. O’NEIL
Director for Research and Engineering

NAWCWD Technical Publication 8791

Published by..... Technical Communication Office
Collation..... Cover, 11 leaves
First Printing 22 paper, 23 electronic media

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.					
1. REPORT DATE (DD-MM-YYYY) 08-09-2015		2. REPORT TYPE Final		3. DATES COVERED (From - To) 1 March 2015 –28 August 2015	
4. TITLE AND SUBTITLE On Acceptable Exposures to Short Pulses of Electromagnetic Fields (U)				5a. CONTRACT NUMBER N/A	
				5b. GRANT NUMBER N/A	
				5c. PROGRAM ELEMENT NUMBER N/A	
6. AUTHOR(S) Francis X. Canning, PhD				5d. PROJECT NUMBER N/A	
				5e. TASK NUMBER N/A	
				5f. WORK UNIT NUMBER N/A	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Air Warfare Center Weapons Division 1 Administration Circle China Lake, California 93555-6100				8. PERFORMING ORGANIZATION REPORT NUMBER NAWCWD TP 8791	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Air Warfare Center Weapons Division 1 Administration Circle China Lake, California 93555-6100				10. SPONSOR/MONITOR'S ACRONYM(S) NAWCWD	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) N/A	
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release.					
13. SUPPLEMENTARY NOTES None					
14. ABSTRACT (U) This report presents a targeted survey of standards and other research on the safety to humans of short pulses of electromagnetic radiation. Special attention is paid to a ten nanosecond pulse allowing a comparison of the permitted power levels according to various standards and recent research. This report notes that power levels allowed by IEEE standards have, in some cases, changed by several orders of magnitude over recent years. Recent research is presented showing that the adequacy of current standards is far from a settled issue.					
15. SUBJECT TERMS International Commission on Non-Ionizing Radiation Protection, Institute of Electrical and Electronics Engineers, maximum permissible exposure, nerve excitation, radiation exposure standards, short pulses					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 20	19a. NAME OF RESPONSIBLE PERSON Francis Canning
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (include area code) (760) 428-4442

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

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INTRODUCTION

This report presents the results of a targeted survey of information on acceptable levels of exposure to short pulses of electromagnetic energy. It considers exposures due to fields transmitted through the air and not those due to direct contact with wires or other conductors. For these short pulses the report describes relevant standards, relevant guidelines, and research on the effects of this radiation.

The goal of this report is to give an overview of current and past standards and guidelines, to show their similarities and differences, and to compare them to other safety studies for the case of very short pulses. This comparison is important because current standards from different organizations allow power levels differing by several orders of magnitude. Furthermore, one case is described where an Institute of Electrical and Electronics (IEEE) standard was not changed until over fifteen years after published research documented that it was unsafe. For a pulse at 100 kilohertz (kHz) (of duration 5 microseconds [μ s]) and low repetition rate, that change added a nerve stimulation limit that was a factor of one million smaller in power than the previous standard based only on heating effects.

For simplicity, this report concentrates on one specific case. This allows numerical values of the acceptable values according to different standards and guidelines to be compared. This example and the references used should aid others in computing the values allowed by various standards and guidelines for other cases.

The showcase problem considered here is a pulse of length $1\text{E-}8$ seconds (i.e., ten nanoseconds), which is repeated once a second. This will be assumed to produce radiation at 50 megahertz (MHz). Past and current IEEE standards are applied to such a pulse to find the allowable exposure level. Two research studies from 10 years ago are described that cast some doubt on the safety of the allowable exposure level under the current IEEE standard. An international standard is discussed that is significantly more restrictive than the current IEEE standard.

Fifty MHz corresponds to a wavelength of 6 meters (m). Thus, for a distance greater than 1 or 2 meters from a source, the electric and magnetic fields are approximately related to each other in the same way as in a radiating wave far from the source. That relationship will be assumed in this report except where it is explicitly stated that this relationship is not assumed.

LIMIT SET BY 2005 IEEE STANDARD

IEEE Standard C95.1-2005, Reference 1 provides a Maximum Permissible Exposure (MPE) for the pulse under consideration. The MPE is defined in 3.1.39as, “The highest RMS or peak electric or magnetic field strengths...to which a person may be exposed without incurring an established adverse health effect and with an acceptable margin of safety....” For the full definition, see Reference 1, page 8, paragraph 3.1.39. Regarding the IEEE standard and other standards and guidelines, the description given here is necessarily significantly abbreviated. For the full standards and guidelines, please see the references cited.

Table 8 in IEEE Standard C95.1- (2005) gives the “MPE for the upper tier (people in controlled environments).” Table 9 gives the “Action Level (MPE for the general Public when an RF safety program is unavailable)” (see Reference 1, pages 24 and 25). The information in Table 8 is presented graphically in Figure 3 of this reference. For the showcase pulse and a controlled environment, the MPE is a root mean square (RMS) field strength of 61.4 volts per meter (V/m) when the square of the field strength (which is proportional to power) is averaged over 6 minutes. Since the duty cycle of the pulse is considered to be 1 part in 1E-8, the power is increased by a factor of 1E-8. Equivalently, the electric field strength is increased by 1E-4. Thus, the instantaneous MPE becomes 6.14E5 V/m, or 614 kilovolts per meter (kV/m). This limit will be referred to as a heating limit.

Tables 8 and 9 contain notes that provide additional restrictions. Note “e” states, “For exposures to pulsed RF fields, in the range of 100 kHz to 300 GHz, the peak (temporal) value of the MPE for the instantaneous E field is 100 kV/m.”

Note “f” provides a limit that must be computed. The note states, “... the total incident energy density during any one-tenth second period within the averaging time shall not exceed one-fifth of the total energy density permitted during the entire averaging time for a continuous field...” This limit is not very stringent for a very short pulse. If Fallow is used to denote the V/m allowed by note “f” during the short pulse, then since the averaging time is 6 minutes; $(F_{allow})^2 = 61.4^2 * 360 \text{ seconds} / (5 * 10^{-8} \text{ seconds})$. Thus, for the pulse considered here, Fallow is 5.2E6 for a limit of 5,200 kV/m. In summary, the most stringent limit is given by note “e” with an MPE of 100 kV/m. Note that this limit is within a factor of ten of where air may become ionized and start to conduct current. This will loosely be referred to as the air ionization limit in this report (regardless of whether that was the actual reason for this limit).

Department of Defense Instruction (DoDI) 6055.11 (2009) addresses allowable exposures (Reference 2). This instruction generally follows C95.1-2005 (Reference 1), enclosure 3, part 1a. However, part 1b states that the maximum MPE for pulses is 200 kV/m, in contrast to the 100 kV/m air ionization limit of C95.1.

As described in the next section, there has long been reason to believe that C95.1-2005 and the DoD Instruction, Reference 2 (that generally follows Reference 1), do not offer sufficient protection for certain short pulses. Nevertheless, Reference 2, Enclosure 3, Part 1c states, “When developing EMF safety programs, do not apply additional safety margins. The MPE limits in this Instruction incorporate adequate safety margins.”

NERVE STIMULATION LIMITS

C95.1-2005 is based primarily on avoiding heating effects. However, it is known that strong magnetic fields can directly excite nerves, which is apparently not considered in C95.1. Reference 3 describes the nerve excitation limits the Food and Drug Administration (FDA) applies to magnetic resonance imaging (MRI) machines and shows that in many cases they are much more stringent than those in C95.1-2005. Reference 3 was authored by J. Patrick Reilly, arguably the most prominent expert in this field. Page 137 of Reilly’s paper states, “In order to avoid nerve stimulation from pulsed fields, it is necessary to impose a constraint on the peak value of the allowable field. Since pulsed field limits for avoidance of nerve stimulation have already been specified for magnetic resonance imaging (MRI) exposure, it is worth considering the application of MRI criteria to IEEE/ANSI standards.” Furthermore, the report states, “...the U.S. Food and Drug Administration (FDA) supported the development of guidelines intended to avoid peripheral nerve stimulation during MRI examinations [2]. These guidelines were subsequently adopted by the FDA as advisory safety criteria for patient exposure to switched-gradient fields [4]. A second study commissioned by the FDA lead to the development of guidelines for avoidance of cardiac excitation via switched-gradient fields [4]....”

Figure 1 in Reference 3 displays the field strengths where one would first feel nerve excitation (often in the forearm) and the limits where 50 percent of people would have direct cardiac excitation. For the range of frequencies shown (which are several orders of magnitude smaller than the 50 MHz for the showcase pulse) the 50 percent heart excitation took a field strength of 50 or 100 times larger than the peripheral nerve excitation. This is not surprising since less radiation would penetrate to the cardiac nerves than forearm nerves since cardiac nerves are deeper within the body.

Figure 3 in Reference 3 compares the nerve stimulation limit to the heating limit in effect at that time, which is the same as that of C95.1-2005 (Reference 1). It is important to note that Reference 3 does not make the assumption that the electric and magnetic fields are related as they are in a travelling wave. In an MRI machine the patient may be less than 1 meter from the antenna, and the antenna may even extend around the patient. Furthermore, the frequency transmitted by MRI machine is a few orders of magnitude smaller than at 50 MHz, so the wavelength is a few orders of magnitude larger. Thus, these large magnetic fields could be excited without the air ionization limit coming into play.

Consider an MRI machine at 50 kHz with a pulse of 1E-5 seconds (10 μ s) repeated once a second (this is different from the showcase problem considered in this report). Since essentially only a magnetic field is produced in such a machine, the field strength permitted by Reference 1 would, according to Figure 1 in Reference 3, produce direct cardiac excitation in 50 percent of people. Also, according to Reference 3, Figure 3 (remembering the 1E-5 duty cycle here), this pulse would be within the C95.1-2005 standard. Although C95.1-2005 (and DoDI 6055.11) permits this exposure, it is highly hazardous. Thus, although C95.1-2005 may be a necessary standard to follow, it clearly is not a sufficient standard for safety.

Until late 2014, DoDI 6055.11 (Reference 2) did not allow DoD safety programs to take into account J. Patrick Reilly's paper on nerve stimulation limits from 1998 (Reference 3). In late 2014, IEEE standard C95.1-2345-2014 (Reference 4) was published. This standard does include restrictions to limit nerve stimulation and removes the air ionization limit. For a pulse at 100 kHz (20 μ s long) repeated once a second, the previously known nerve stimulation limit reduces the allowable power level of an exposure by a factor of 250,000 times from that of the heating limit in C95.1-2005 (Reference 1). Reference 4 also provides a more conservative nerve stimulation limit than Reference 3, so it adds a nerve stimulation limit to the standard that is one million times smaller in power than the previous limit which was a heating limit.

Although C95.1-2345-2014 (Reference 4) imposes restrictions to limit nerve excitation, those restrictions only apply up to 5 MHz (or to pulses shorter than 1E-7 seconds). Of interest in the present report are pulses shorter than 1E-7 seconds. The current IEEE (military) standard does not provide any nerve excitation limit for such pulses. Thus, the rest of this section addresses what Reilly's 1998 paper says about such short pulses. In later sections of the present report, the results of several other research papers on this topic are presented. For the purposes of the present report, it is only prudent to consider published known hazards for very short pulses, since there is a history of IEEE standards lagging published known hazards by almost 2 decades.

Figure 3 in Reilly's paper, Reference 3, shows a nerve stimulation limit of 0.76 mT (milliTesla) for frequencies from 3 kHz up to 1 MHz, where the graph ends. Note that this maximum is independent of duty cycle. Reference 3, page 140 states, "The question arises: how far in frequency can we extend the plateau shown in Figure 3? ...And from human sensory experiments with brief current pulses, one could infer experimental correspondence to perhaps 10 MHz." Thus, there is evidence for a nerve stimulation limit of 0.76 mT for frequencies from 3 kHz up to 10 MHz. Our showcase pulse concerns a frequency of 50 MHz. Since there is little or no evidence (see the section on Animal Studies below) that the limit for nerve stimulation changes between 10 MHz and 50 MHz, the most reasonable assumption is that the nerve stimulation limit should still be 0.76 mT at 50 MHz (according to Reference 3 or at 0.205 mT according to C95.1-2345-2014). Further evidence supporting this will be presented in later sections.

Again, considering the showcase pulse of 50 MHz that is repeated once per second, it is found that the nerve stimulation limit from Reilly's paper (Reference 3), if that limit is applied at 50 MHz, gives:

$$0.76 \times 10^{-3} \times \frac{\text{Volt seconds}}{\text{meters}^2} = \frac{\text{Enerve}}{3 \times 10^8 \text{meters/second}} \quad (1)$$

$$\text{Enerve} = 228 \text{ kV/meter}$$

This is more restrictive than the heating limits from any of the IEEE standards.

LIMIT SET BY 2014 IEEE STANDARD

IEEE Standard C95.1-2345-2014 (Reference 4) only became available in late 2014. Apparently, a DoDI directing its use has not yet been issued. This is not surprising since after C95.1-2005, it took 4 years for a DoDI directing its use to be issued (Reference 2). This new IEEE standard replaces a previous North Atlantic Treaty Organization (NATO) agreement and, apparently, is also now the NATO standard.

The way the United States sets standards is different from that of much of the rest of the world. Generally (oversimplifying), for the United States to limit the strength of some radiated field, there has to be a documented harmful effect of that field. The standard is generally then set to a power level about ten times smaller. This means that if there is strong reason to believe there is a harmful effect, but it has not been documented by actual instances of harm, then the United States might not have a standard preventing such an exposure. Most of the rest of the world is much more conservative in setting their standards.

As previously mentioned, C95.1-2005 (Reference 1) included a limit of 100 kV/m. That is referred to here as the air ionization limit, since depending on humidity air ionizes at a field strength that can be within an order of magnitude of that limit. The corresponding DoDI 6055.11 replaced this with a limit of 200 kV/m. The new standard, IEEE C95.1-2345-2014 (Reference 4), completely removed these limits from the original standard.

Appropriately, the workplace standard is somewhat more stringent than what is allowed for patients under medical care. Thus, it is not surprising that under IEEE 95.1-2345-2014, the size of the nerve stimulation limit that was adopted is more stringent than that for MRI machines. Rather than 0.76 mT, the 2014 standard says that from 3.35 kHz to 5 MHz, for the head and torso, the limit is 0.205 mT (Table 2, page 27). Thus, updating our calculation at the end of the previous section, we see that if the nerve stimulation limit were applied at this higher frequency, then the allowable exposure to a magnetic field would be 61.5 kV/m. Figure 1 of the 2014 standard (Reference 4) shows a heating limit of 27.5 V/m for a 100 percent duty cycle. Since the showcase pulse has a

duty cycle of 1E-8, the heating limit becomes 275 kV/m. Thus, the nerve stimulation limit is more stringent by over ten times in power even at this frequency.

Note that in the comparisons given in this report, the electric and magnetic field strengths are assumed to be related as for a propagating wave. In the standards, limits are often given separately for the magnetic and electric fields. These limits are always approximately related in the same way, but there are often differences of a factor up to five. As a result, one could reasonably derive numbers somewhat different from those given here, but the differences are relatively small.

In the introductory section, C95.1-2345-2014 states on page 6, Section 1.3.6.2, “However, for pulsed waveforms, especially those of a low duty factor, the upper frequency at which electrostimulation effects have been demonstrated to have lower thresholds than electrical heating effects reaches 5 MHz [B33].” The reference given is to a book by J. Patrick Reilly, published in 1998, that gives essentially the same information as his 1998 paper discussed here as Reference 3. If the nerve stimulation formula were applied to the showcase pulse of 50 MHz, it would be over ten times more restrictive in power than the electrical heating restriction. If this pulse of ten nanoseconds were only repeated once every hundred seconds, then the nerve stimulation guideline would be over one thousand times more restrictive in power. Thus, the position of the 2014 standard is apparently that it has not been proven that there is a nerve stimulation effect above 5 MHz. In a later section, experimental studies will be presented that strongly suggest that nerve stimulation does occur for pulses as short as one nanosecond.

Standard C95.1-2345-2014 provides the option of using either of two methods for computing the maximum exposure limit for a pulse. Section 4.1.2.4.11 uses only one frequency, computed as one half of one over the pulse duration. The single resulting frequency is then used to determine the exposure limit. That method has been used in the discussions up to this point.

An alternative method of determining the maximum exposure under the standard is given in Section 4.1.2.4.2. That section states, “For an exposure waveform consisting of multiple frequencies, a test for compliance of the exposure waveform shall satisfy the following criterion:”

$$\sum_0^{3MHz} \frac{A_i}{ERL_i} \quad (2)$$

Apparently, their intention is that the criterion is that this sum must be less than one for the exposure to be allowable. The text below this in the standard says the summation should be carried out to 5 MHz, which contradicts the 3 MHz in the summation symbol. That text also states, “where A_i is the magnitude of the i^{th} Fourier component of the exposure waveform,...” Since a discrete sum is used (and not an integral), this appears to refer to the elements of a discrete Fourier transform (DFT) of the exposure waveform.

There are several different commonly used definitions of the DFT. They differ from each other in the sign used in the exponent and in their normalization. Since only the magnitude of the elements of the DFT is used, the sign in the exponent is irrelevant. For one such choice of sign, the DFT of a sequence S_n is given by the following:

$$T_m = DFT(S_n) = A \sum_{n=0}^{N-1} \exp\left(\frac{imn}{N}\right) \times S_n \quad (3)$$

Then, the inverse discrete Fourier transform, IDFT, is given by the following:

$$S_n = IDFT(T_m) = B \sum_{m=0}^{N-1} \exp\left(-\frac{imn}{N}\right) \times T_m \quad (4)$$

It is necessary that the product of A and B is given by the following:

$$A \times B = 1/N \quad (5)$$

Within the constraint on the product of the constants A and B given in Equation 5, there are three commonly used definitions of the DFT and its inverse (Table 1).

TABLE 1. Definitions of DFT and IDFT.

Convention Type	Convention
MATLAB	$A = 1; B = 1/N$
SYMMETRIC	$A = 1/\sqrt{N}; B = 1/\sqrt{N}$
C95.1-1234-2014	$A = 1/N; B = 1$

All three of the conventions shown in Table 1 are commonly used. The standard C95.1-2345-2014 is silent on the issue of which convention should be used in computing exposure limits. It is necessary that the third convention shown be used when using C95.1-2345-2014. If either of the other two conventions were used instead, then the criterion described by (2) would give a different result depending on how many terms were used in the DFT. The standard does not specify the interval over which the DFT should be taken, so below, it is assumed that it is taken over the interval where the pulse is non zero.

This criterion will now be discussed for the case of a monophasic pulse. That is, for a pulse that has only a positive voltage. A biphasic pulse would be one with say a positive voltage followed by a negative voltage. The standard appears to have a monophasic pulse in mind since the first criterion gives the appropriate frequency for a monophasic pulse.

Such a monophasic pulse will have a DFT dominated by its zero frequency component. Thus, even for a very high frequency pulse (e.g., GHz or higher), there will always be a resulting limit as if nearly all of this pulse were at zero frequency. For example, for exposures of the head and torso, Table 2 in the standard applies, and the limit will be about 118 mT. One way of looking at this is that because there is only the

first half of a full oscillation, the DFT components look more like zero frequency than the frequency used by the first criteria (Section 4.1.2.4.1 of C95.1-2005).

Consider now a pulse of approximately 100 kHz. Using the first criteria, the exposure reference level (ERL) for the head and torso (Table 2) would be 0.205 mT. Now further assume that the pulse rapidly rises linearly from zero to its maximum in the first two hundredths of a percent of its duration. Let it be constant at that value until it similarly falls to zero at its end. Then the limit using the second criteria computes to about 2.5 mT. This is more stringent than the zero frequency limit.

Similarly, using a rise that is smoother than linear, a pulse can be created where the limit computes to 0.05 mT. Thus, the second method of calculation can give significantly different results that are either larger or smaller. That is, by changing the shape of the beginnings and ends of the pulse, the allowable level of magnetic field changes by a factor of 50, corresponding to a change in power level for a propagating field of a factor of 2,500.

The value of 0.05 mT is not even within the range of values occurring in Table 2 of the standard. It may be surprising that this is possible. It is especially surprising if one chooses to think of the sum in Equation (2) as a type of average, which would not be correct. The reason it is not a type of average is that although the sum of the squares of the A_i is related to the power in the pulse (Parseval's Theorem), there is no such relation for the sum of the A_i s, and it is the sum of the A_i s that occurs in Equation (2). Thus, Equation (2) gives a significantly different result depending on issues that would appear to be irrelevant to the effect of the exposure. Since the sum of the A_i s varies greatly with issues such as how the signal is discretized, etc., it is surprising that the sum of the squares of the A_i s was not used in the formula. The sum of the squares is a conserved quantity.

NERVE STIMULATION RESULTS FOR PULSES FROM 100MS TO 1NS DURATION

There appears to be no available research describing nerve stimulation from exposures to signals propagated through the air that are shorter than $1\text{E-}7$ seconds (100 nanoseconds [ns]). However, for exposure via directly connected electrodes, there is a very careful study that includes pulses as short as one nanosecond (Reference 5). This study required using different equipment for different pulse lengths and is very convincing due to the internal consistency of its results for pulse lengths varying by eight orders of magnitude.

This study used muscles taken from frogs. For each pulse length, the strength of the excitation was increased until muscle movement was observed. Pulse lengths from

100 milliseconds (ms) (one tenth of a second) to 1 ns were used. Then a strength duration curve was plotted.

The strength-duration curve was plotted on a log-log scale. For the portion of this curve showing pulses that were between 100 ms and 1 ns long, this plot showed a straight line. The authors of this report considered this as evidence that the physiological mechanisms did not change for short pulses, even for pulses as short as 1 ns. Current standards, such as IEEE C95.1-2345-2015, implicitly take into account that for radiated pulses, the higher the frequency the more weakly they penetrate into the body. Thus, these results suggest that there is harm up to one half a GHz.

The only way around the conclusion that there is a risk of harm from nerve excitation up to a half a GHz, for pulses with magnetic fields above the C95.1-2345-2014 limit (0.205 mT), would be to assume that the fundamental mechanisms of propagation of short pulses depend on frequency in one way for frequencies up to 5 MHz and then depend on frequency in a different way for higher frequencies. The discussion in that paper (Reference 5) suggests exactly that conclusion. The reason given is that it interprets animal studies of long-term effects and other effects to require that conclusion. Thus, animal studies are discussed in the next section.

An argument as to why high-frequency radiated pulses will not couple into a person is given in Reference 5. The paper argues that the electric field excited in a person will be ten times smaller than that incident on the person, but it does not argue as to why that would only be true at the higher frequencies. Regarding previous radiated field biological studies, the referenced paper also states (page 1,597), “These studies used radiated signals that are inherently biphasic and carried no dc component.” Page 1,589 states, “A monophasic pulse cannot be radiated; it quickly will become biphasic in the far field....thus, even greater electric field strengths will be required in air to produce changes in tissue sufficient to induce a response.” However, the paper does not explain why this effect would occur above 5 MHz and not below that frequency.

The issue of how short pulses in the air produce electric fields in dielectric materials, including in humans, is surprisingly complicated. For nearly a century, it has been known that within a dielectric medium, precursors form at the forward edge of the pulse. The pioneering research from a century ago suggested that the precursors carried very little energy. More recently, however, it has become accepted that there was a misconception in the previous calculations and that, for short pulses with large bandwidth, precursors can carry roughly half of the total energy. In addition, it has been shown that some precursors propagate with no energy lost to absorption, even in lossy dielectrics. Within a dielectric body (e.g., within a person), the shape of the signal is very different from the short pulse that travelled through the air.

One of the primary authors of work on precursors is Kurt Oughstun. One of his papers, which was supported by the Air Force Office of Scientific Research, is given here as Reference 6. The summary in that paper states in part, “The application of

dispersion-matched precursor pulses to ground and foliage penetrating radars as well as to imaging through multilayered walls and biological structures (e.g., for tumor detection) promises greatly improved system performance. As such, their impact on non-ionizing radiation safety standards remains to be considered.” For Figure 1 in Reilly’s paper (Reference 3), it appears that a magnetic field is attenuated by a factor of 50 or so from near the skin to the heart. Thus, when precursors are present that have very little attenuation, standards would have to be adjusted significantly. The issue of precursors is considered in more detail in the section on the National Academies research study.

ANIMAL STUDIES OF THE EFFECTS OF SHORT PULSES

Chapter 4 of the “Radio Frequency Radiation Dosimetry Handbook” from the Air Force Research Laboratory (Reference 7) is titled, “Review of Literature on Biological Effects of High Peak Power (HPP) Pulses, Electromagnetic Pulse (EMP), and Ultra-Wideband (UWB) Pulses.” Most of the studies reported in that chapter found no effect from short pulses. Note that many of these studies used low power levels. Also, most of these studies looked only for some specific effect and often only for an effect that occurred after the exposure ended. However, some studies did still show some effect. Notably, page 109 of Reference 7 reported on one such study:

“In a more recent report using free-field exposure, rats and rabbits were exposed to 1 to 2 ns, 10 to 13 kV/m UWB pulses at 6 Hz for 1 h (Petrova et al., 2005). Immediately after exposure, the EEG of exposed rats exhibited differences in spectral content, particularly at frequencies near the pulse repetition frequency of 6 Hz. Information sufficient to judge the significance of the differences was not reported. The EEG along with electromyogram (EMG) of exposed rabbits was followed for more than 21 h after exposure. Beginning at about 18 h after exposure, the animals showed differences in sleep EEG patterns relative to controls. The differences included increased duration of slow sleep and paradoxical sleep.”

The pulses that these animals received are treated very similarly under C95.1-2345-2014 as the showcase pulse. For example, the C95.1-2345-2014 heating limit for such a nanosecond pulse is about 65% of the heating limit for our standard pulse. On the scale of comparisons made in this report, that is a very small difference. Thus, these experiments on rats and rabbits should approximately apply to our showcase pulse. Of more significant concern is that these abnormalities in rats and rabbits were found at 10 to 13-kV/m, while the C95.1-2005 heating limit is 275 kV/m for the standard pulse (Table 9 or Figure 2 of Reference 4). The power level that caused these effects in rats and rabbits is over 500 times less than that allowed by the current IEEE standard.

ICNIRP GUIDELINES

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has produced guidelines for exposures to electromagnetic fields (Reference 8). In many cases, these guidelines follow C95.1-2005 and C95.1-2345-2014 (References 1 and 4). However, there is a significant difference for the case of short pulses.

Table 6 of the ICNIRP guidelines gives a limit of 61 (V/m) (RMS) for our showcase 50 MHz pulse, while Table 8 of C95.1-2345-2014 gives a limit of 61.4 (V/m). However, Note 5 to Table 6 of the ICNIRP guidelines states, “For peak values at frequencies exceeding 100 kHz see Figs. 1 and 2. ...For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1,000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.”

Thus, multiplying 61 V/m by 32 gives a limit of 1.95 kV/m. Figure 1 of the ICNIRP guidelines also shows 1.95 kV/m at 100 MHz as the peak occupational exposure. Note that the ICNIRP guidelines treat pulses very differently from C95.1-2345-2014 and, thus, give a much lower acceptable peak exposure value. Indeed, the C95.1-2345-2014 limit for this pulse is 275 kV/m. The ICNIRP guideline allows about 20,000 times less power than does C95.1-2345-2014.

RESEARCH STUDY BY THE NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES

“In a January 11, 2011, letter from Senator Edward M. Kennedy to the Secretary of the Air Force, F. Whitten Peters, Senator Kennedy asked that the Air Force fund an independent study through the National Research Council of the National Academies ‘to examine the health effects of the PAVE PAWS system.’... The offices of Senators Kennedy and Kerry and Congressman Delehunt, participated in discussions with the Air Force and the National Research Council to establish the task that is addressed by this committee in this report.” (See Reference 9, Preface.)

This is one of the most careful studies of the effects of radio frequency radiation that has ever been performed. There were 11 prestigious committee members, multiple open hearings, and 2 trips to Air Force facilities to search for classified information on

radiation effects. Senator Kennedy spoke at the final open hearing (Reference 10). The PAVE PAWS radar is in the Cape Cod region of Massachusetts.

The PAVE PAWS radar had been in use for about 20 years, resulting in a prolonged exposure to the public. However, as compared to the peak power allowed by IEEE Standard C95.3-2345-2014 for the showcase pulse, the public was exposed to a peak power from the PAVE PAWS that was lower by fourteen orders of magnitude or more. Thus, it is not surprising that this study found no harmful effects from this radar. However, there are two issues that they examined carefully and their reasoning and conclusions on these two issues are useful.

The committee found some previous research that suggested pulse repetition rates of roughly 10 to 100 Hz could affect the dopamine levels of persons and other animals. Note that in Reference 7 an effect was found on rats and rabbits for a pulse repetition rate of 6 Hz. Thus, one must consider the possibility that the effect shown in Reference 7 was not due to nerve excitation. This type of information provides a caution that seemingly contradictory experimental results may actually not be contradictory but be due to variables that were not controlled. Thus, the results of Reference 7 cannot be ignored just because other experiments using the same peak V/m found a different result.

There is a second issue that was given careful consideration by the committee, that of precursors. From the outset, the committee was aware of this issue. In fact the leading researcher in this field, Kurt E. Oughstun from the University of Vermont, was one of the committee members. The definitive work on this subject is his book (Reference 11). The vice-chairman of the committee personally spent a significant amount of time studying this subject and became convinced of its correctness (Reference 10). The committee concluded that the presence of precursors depends on the bandwidth of the signal and the dispersion of the propagation medium but not on the strength of the signal (as in V/m). They also concluded that for the 5 percent bandwidth of the PAVE PAWS radar, and for the dispersion in a person (who is primarily water), precursors would not play a significant role. However, they further concluded that for a significantly larger bandwidth, precursors would be likely to play an important role. For the types of pulses considered in this report, the bandwidth is significantly larger than 5 percent. It is often 50 percent or more.

The definition of a dispersive medium is that different frequencies propagate at different speeds. Large bandwidth means that there are significantly different frequencies present, which then propagate at different speeds through the medium. For a short pulse, this results in the pulse significantly changing shape as it propagates. In this case, the shape changes until a mature (constant) shape is formed, the first part of which is called a precursor. The precursor can have over half of the total energy of the propagating pulse. When looked at locally, these precursors can have a very slow (essentially zero) rate of phase change. Most importantly, they can propagate without any loss even in what would otherwise be considered a lossy medium. It should be stressed that there is a theory of precursors that can be used to evaluate them for any given pulse shape. However, the

bandwidth is the most important factor for a given material's dispersion. This theory has been established both theoretically and experimentally (Reference 12).

If we revisit Reilly's paper (Reference 3), it can be seen that his data indicates that the field strength reaching the heart is reduced by a factor of 50 or 100 from that reaching the nerves in a person's forearm. Precursor theory suggests that for an appropriately shaped very broadband pulse, the field strength at the heart might be only two times weaker than near the surface. Thus, there is some reason to consider a nerve excitation standard that is correspondingly stricter than it would be without precursors. Such a standard would have an allowable excitation that is reduced by a factor of 50 in field strength or a factor of 2,500 in power from what it would be if precursors were not considered.

SUMMARY

Safety issues for exposure of humans to short pulses of electromagnetic radiation have been considered. Considerations for implanted medical devices and implanted metal objects and the like are outside the scope of this report. Past standards and current standards have been compared to each other and to some of the more pertinent research on the safety of these exposures. Hopefully, the reader will find it abundantly clear that although there are standards, the appropriateness of those standards is not a settled issue.

It was shown that application of the previous IEEE standard, C95.1-2005 (Reference 1), and the associated DoD instruction to a pulse 10 μ s long and repeated once per second gave an allowable strength that would produce cardiac arrhythmias in 50 percent of people. This was well understood at least as far back as 1998, yet it was not until late 2014 when IEEE Standard C95.1-2345-2014 was issued that this oversight was corrected. It implemented new nerve stimulation limits that reduced the allowable power level for such a pulse by a factor of one million times.

This report primarily considers a showcase pulse, which is 1E-8 seconds (ten nanoseconds) long and is repeated once per second. The nerve stimulation limits implemented in C95.1-2345-2014 only apply up to 5 MHz or equivalently to pulses longer than 1E-7 seconds (100 ns). Research was presented that suggests that these nerve stimulation limits should be applied to pulses at least as short as 1 ns.

Figure 1 summarizes the major findings of this report. This figure describes the various possible allowable levels of exposure to the showcase pulse considered in this report. That pulse is 10 ns long and is repeated once per second. It is assumed that the exposure occurs more than a meter from the source so that the electric and magnetic fields are approximately related as they are in the far field of that source.

Figure 1 shows that the power level permitted by C95.1-2345-2014 for this pulse is nearly twenty thousand times greater than that allowed by the standard from the ICNIRP. MRI machines do not produce pulses as short as 10 ns. However, if the FDA guideline for MRI machines is applied at this frequency, it gives a limit for exposures that is several times lower in power than does C95.1-2345-2014. If the nerve stimulation limit of C95.1-2345-2014 is applied to this pulse, it gives a limit over ten times lower in power than the result actually given by C95.1-2345-2014 (which is a heating limit). The next smaller number shown on Figure 1 is the results of one animal study. One can argue whether other animal studies contradict this result or whether those studies were looking for different effects so there is no contradiction. However, a study with rats and rabbits, using a very similar pulse to the showcase pulse, showed EEG and sleep abnormalities for nearly a day after exposure. The power level of this exposure was over 500 times lower than that permitted by C95.1-2345-2014 (which is a heating limit). Finally, one may take the nerve stimulation limit from C95.1-2345-2014, choose to apply it at this higher frequency, and then also assume that precursors cause little decay for fields moving through the body to the heart. The resulting limit is 1.3 kV/m, which is slightly more stringent than the ICNIRP standard. What is significant is that, as compared to the official standard for the military in the US, C95.1-2345-2014, reasonable arguments can be made for a standard that is stricter in power levels by from two to five orders of magnitude. Note that this is a military standard, and not the general IEEE standard.

All of the discussion in this report was presented in a compact format. Each of the references should be read to supply further details and to understand how the various standards and guidelines were applied. For short pulses of about 10 ns, there is significant tension between C95.1-2345-2014 and the ICNIRP guideline (Reference 4 and 8). These standards differ by a factor of nearly 20,000 in power. In addition, although we have an official standard, the issue of whether the nerve stimulation limits should be applied for pulses shorter than 100 ns is not well settled, and it alone could reduce allowable power levels by a factor of 100 for a pulse repeated once per second. The reductions would be even greater for pulses that are repeated less often. Finally, even IEEE Standard C95.1-2345-2014 itself is internally ambiguous. All of the results shown in Figure 1 assumed that the first method given in the report for computing the frequency of a pulse is used. However, there is an alternative method given in the report, that can give exposure limits that are either much larger or smaller than the first method, depending on minute details of the pulse shape that do not appear to be relevant. In the face of these varying standards, abundant caution may be appropriate.

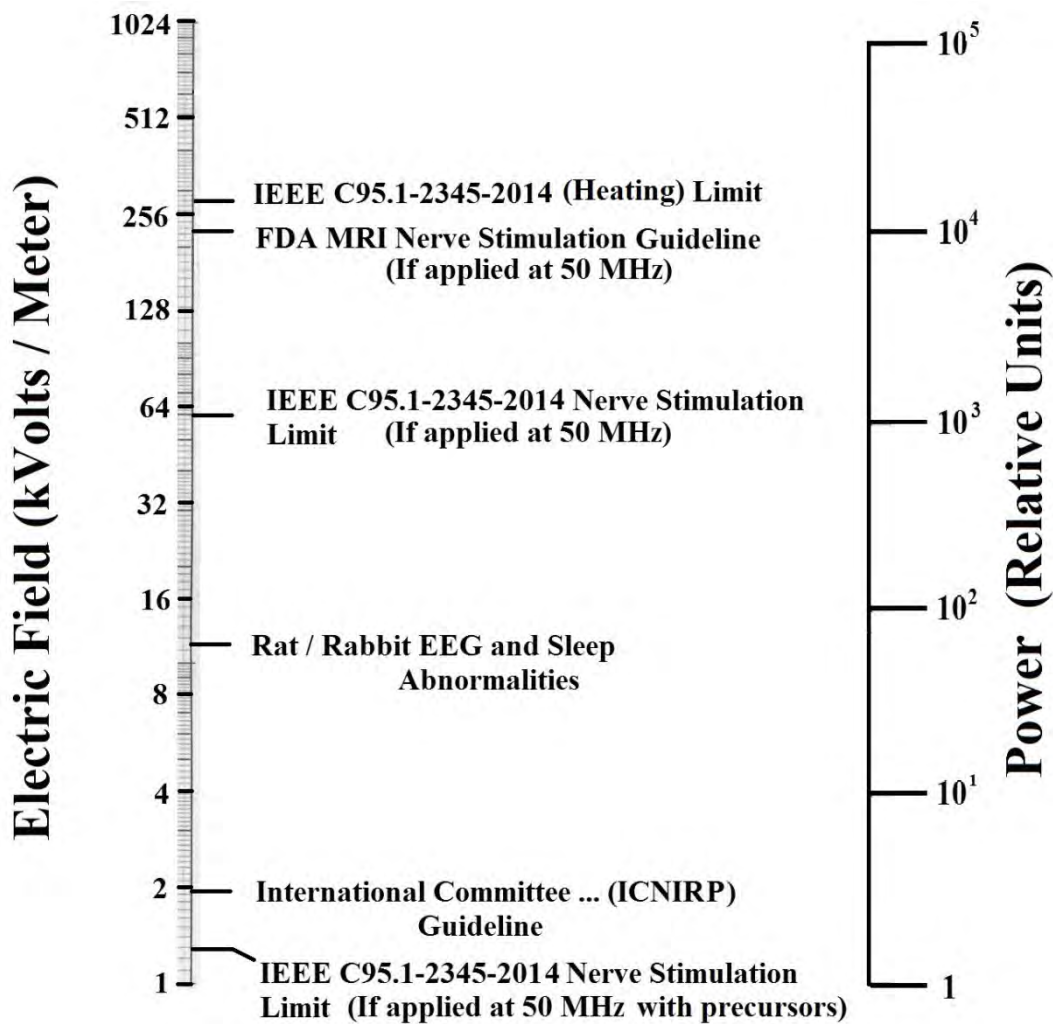


Figure 1. The Electric Field Strength that is allowed by various standards / that produces stated effects, for a pulse that is $1\text{E}-8$ seconds (10 nanoseconds) long and that is repeated once per second.

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NOMENCLATURE

ANSI	American National Standards Institute
DFT	discrete fourier transform
DoD	Department of Defense
DoDI	Department of Defense Instruction
EEG	electroencephalogram
EMP	electromagnetic pulse
ERL	exposure reference level
FDA	Food and Drug Administration
GHz	gigahertz
HPP	high peak power
Hz	hertz
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
kHz	kilohertz
kV/m	kilovolts per meter
m	meters
MHz	megahertz
MPE	maximum permissible exposure
MRI	Magnetic Resonance Imaging
mT	milliTesla
NATO	North Atlantic Treaty Organization
ns	nanosecond
RF	radio frequency
RMS	root mean square
UWB	ultra-wideband
V/m	volts per meter
μs	microseconds

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