PHYSICAL QUANTITIES AND RISK ASSESSMENT CRITERIA

FOR EXPOSURE TO EMF[1]

1 - INTRODUCTION

The main physical quantities involved in the process of assessing human exposure to electromagnetic fields (EMF) are first of all the well-known fundamental quantities of the electromagnetic field itself: the **electric field E** (which describes the interaction between electric charges), the **magnetic field H** or **magnetic induction B** (which concern the interaction between moving charges and therefore between electric currents) and the **power density S** (which measures the energy transported by an electromagnetic wave per unit of time and unit of surface crossed). To these are added the quantities induced by the field in the tissues of the exposed organism: the **electric current** flowing in them and the power deposited, measured by the **SAR** (*Specific Absorpion Rate)* parameter. Finally, it is necessary to take into account the **exposure indices,** which are necessary in particular for the assessment of exposure to fields with a non-sinusoidal waveform.

A good starting point for discussing the role of these quantities in the exposure assessment process is provided by international "science-based" *guidelines*.

Starting from consolidated assumptions and applying the most rigorous possible logical and mathematical processes, they arrive at formulating:

- the **safety limits,** i.e. the maximum values of the physical quantities involved, which must not be exceeded if one wishes to prevent the unwanted effects of exposure;
- the **metric** with which to evaluate compliance with these limits, that is, for example, how to take into account the variation in space and time or the spectral content of the quantities considered.

Here we will refer, in particular, to the *guidelines* of the **International Commission on Non-Ionizing Radiation Protection** (ICNIRP, www.icnirp.org) [1,2,3,4,5] which, as is known, represent one of the most authoritative normative sources currently available; they also constitute the scientific basis of the provisions on the matter issued by the institutions of the Community or the European Union [6,7].

The guidelines are complemented by *technical standards* (such as the IEC/CENELEC standards, see for example [8,9]), which provide indications through which to give practical application to the process of verifying compliance with the *safety limits* indicated by the guidelines, in compliance with the evaluation *metric* appropriate from time to time.

Evaluating the risk associated with an individual's exposure to an electromagnetic field therefore means determining – through measurements or calculations – the value assumed by the physical quantities indicated in the regulations, adopting measurement and/or processing

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procedures compliant with the required metrics, so as to be able to then compare the result obtained with the limit value specified in the regulations themselves.

2 - THE SCIENTIFIC RATIONALE OF THE REGULATIONS

The "rationale" of the regulations includes the scientific assumptions and methodological paths on the basis of which they were constructed. In the ICNIRP context, the fundamental points of the rationale include: (1) the distinction between professionally exposed workers and the general population; (2) the effects-based approach; (3) the articulation on two evaluation levels.

2.1 - DISTINCTION BETWEEN EXPOSED WORKERS AND THE GENERAL POPULATION

The almost universally accepted regulatory framework (not only within the ICNIRP framework) provides for greater protection (i.e. with *lower limit values)* for the **general population** compared to **professionally exposed workers,** taking into account both the health checks that the law requires to be carried out in the workplace and the presence – among the general population – of people unaware of the exposure they have suffered and belonging to categories considered particularly sensitive (children, the elderly, individuals who are not in good health).

A *professionally exposed worker* should be understood as someone who is assigned to a task that **necessarily involves** exposure to EMF, while all other workers should be treated like the general population. In this regard, the current risk assessment and reduction procedures (see for example [9]) require a **zoning** to be created in workplaces, distinguishing areas in which:

- the limit values for the protection of the general population are respected and therefore access is permitted to anyone without limitations;
- the limit values for the general population are not respected, but those for professionally exposed workers are and therefore access is permitted only to the latter; they are assumed to be:
    - of working age, in good health and suitable to operate in the presence of intense electromagnetic fields,
    - aware of the exposure suffered and informed about the presence and location of the sources,
    - trained to limit exposure and deal with any consequences of accidental overexposure,
    - subjected to regular health surveillance;
- even the limit values for the protection of professionally exposed workers are not respected and therefore access should, as a rule, be denied to anyone.

Furthermore, even in places reserved for workers only, population limits should be taken as a reference for the protection of particularly sensitive workers, such as those with implanted medical devices.

These considerations lead to the conclusion that *the limit values specified for the general population are also relevant in the workplace* and will therefore be presented and discussed below, alongside the limit values and specific requirements for occupational exposures.

2.2 - EFFECTS BASED SETUP

EMF protection regulations aim to prevent the possibility that human beings are exposed to field levels so intense as to cause **biological or health effects**. A *biological effect* is a morphological or functional variation in the tissues, organs or systems of the exposed organism; the effect becomes *health-related* when it involves a pathological alteration of the state of health. A distinction is made between two classes of effects: **short-term effects** (which can be **direct** or **indirect**) and **long-term effects**.

The ICNIRP guidelines aim at preventing *short-term direct effects* (also called **acute effects)**, for which there is sufficient scientific evidence and detailed knowledge to construct safety limits. In fact, for *acute effects*, the following are known: the mechanisms of action, the physical quantities involved, the relative thresholds as a function of frequency, and the dose-response relationships. As we will see, acute effects can in turn be divided into three types: **nausea or dizziness-inducing effects;** stimulation effects **of electrically excitable tissues; heating** (or **thermal)** effects.

2.2.1 - Acute effects

Safety standards are *organized according to the acute effects that are to be prevented* : there are standards for the prevention of stimulation effects, standards for the prevention of heating effects, etc. Simply put, for each effect the relative standard identifies the physical quantity (called **dosimetric quantity)** most suitable for describing the biophysical interaction from which it is generated, identifies the threshold at which the effect manifests itself (usually variable as a function of frequency), applies a suitable margin of caution to it and thus determines the level not to be exceeded in order to prevent the manifestation of the effect itself. In many cases, the *dosimetric quantity* is a physical quantity induced **within** the exposed organism.

Table 1 reports the main effects taken into consideration by the ICNIRP guidelines, indicating for each one the reference *dosimetric quantity and the frequency interval (in a schematic and conventional way) in which the effect itself manifests itself.*

Table 1- Types of effects taken into account by safety standards, reference dosimetric quantities and (conventional) frequency ranges in which each effect occurs.

Effect	Dosimetric magnitude	Frequency range
Induction of nausea or dizziness	External magnetic induction B and its variation ΔB on B over 3 seconds	From 0 to 1 Hz
Stimulation of electrically excitable tissues	Field E internal	From 0 to 10 MHz
Heating	Internal Specific Absorption Rate (SAR)	From 100 kHz to 300 GHz

As a consequence of this setting, it is possible that in a certain frequency range (in which two or more different effects occur) more than one safety limit is specified. Obviously, all other parameters being equal, the lowest limit should prevail, but in reality different evaluation *metrics are often applied to the different effects* (different temporal averaging or complex signal processing methods) which means that the situation is not so trivial. For example, between 100 kHz and 10 MHz both stimulation effects and heating effects can occur. The former, as the frequency increases, tend to have higher thresholds than the latter; for thermal effects, however, the exposure levels *averaged over 6 minutes are relevant,* while for stimulation effects, the *instantaneous levels are relevant*. In the case of intermittent exposure, it is therefore perfectly possible that the limits for stimulation effects end up being more restrictive.

2.2.2 - Indirect effects of electromagnetic fields

Short-term indirect effects are the consequences of the interaction of EMF with passive metal prostheses or active electronic devices implanted in the body of the exposed subject. Often, the product standards of these devices indicate in the 1998 ICNIRP reference levels [2] for the population the limit values below which the devices themselves are able to function correctly. For their part, radiation protection regulations are limited to warning the interested parties and providing rather generic indications. Generally speaking, it is believed that compliance with the limits set for the *general population* is a sufficient condition to guarantee the safety of workers with implanted devices exposed to electromagnetic fields, however, this statement is not explicitly confirmed on a formal level, nor guaranteed on a technical level, and should therefore be considered with caution.

2.2.3 - Long-term effects

Long-term effects are related to very prolonged ("chronic") exposure to EMFs of intensity lower than the thresholds for the onset of acute effects. Although the occurrence of effects of this type cannot be excluded, it is not considered scientifically proven, since the available evidence, especially of an epidemiological nature, is considered inconclusive. They are therefore not included in the logical process of defining safety limits.

2.3 - STRUCTURE ON TWO EVALUATION PLANES

The *rationale* behind the ICNIRP guidelines calls for two separate "evaluation plans" for safety limits.

The first of these is directly linked to the thresholds for the onset of acute effects. In this case, exposure limits are formulated in terms of *dosimetric quantities* representing the effects considered (defined in Table 1). Limits of this type (which ICNIRP calls **basic restrictions)** are obtained by applying appropriate safety factors to the effect thresholds, i.e. reduction coefficients of the order of 5 or 10 times, introduced to take into account the overall uncertainties and individual variability of the thresholds themselves.

In cases where the *dosimetric quantities* are internal to the organism (and therefore not easily measurable), the standards also provide – and this is the second "evaluation level" – limitations in terms of **radiometric quantities** external to the individual (and therefore accessible to measurement): the "unperturbed" *electric field,* the *magnetic field* and the *power density* (i.e. determined in the absence of the exposed subject). The limits that ICNIRP proposes for these quantities are called **reference levels;** they are identified starting from the *basic restrictions* using appropriate mathematical models, called **dosimetric models** and available in scientific literature. The *dosimetric models* simulate the conditions of maximum coupling of the field with the exposed organism and therefore provide the maximum possible protection. In other words, in the process of defining the *reference levels,* further safety margins are introduced that are largely precautionary, so as to ensure that compliance with the levels themselves certainly implies compliance with the *basic restrictions;* on the contrary, the *reference levels could be exceeded without the basic restrictions* being exceeded.

As a consequence of this approach, the ICNIRP guidelines provide for a two-step compliance verification process.

The first step is aimed at ascertaining that the *reference levels are respected* by determining the intensity of the unperturbed *radiometric quantities,* evaluated with the metric specified by the standard. If this condition is verified, the exposure is considered safe. Otherwise, it is possible to decide to immediately apply the appropriate exposure reduction techniques or to resort to the second step; this consists in verifying compliance with the *basic restrictions,* to be carried out through theoretical prediction methods based on the use of appropriate *numerical dosimetry models.* If the *basic restrictions* are respected, then the exposure is considered safe despite the *reference levels being violated.* The second step is not mandatory but may be implemented if three conditions occur: (1) a violation of the *reference levels is found, (2) the reduction to compliance is complex or very costly and (3) there are elements that suggest that the basic restrictions* can be respected. The issue must be carefully assessed, because it is perfectly possible that the second step may in turn detect a violation of the *basic restrictions as well,* thus making the use of mitigation interventions inevitable.

Table 2- Names (in Italian) of safety limits according to ICNIRP guidelines and according to the regulatory provisions of the European Union.

Regulations	**Limits in terms of dosimetric quantities**	**Limits in terms of radiometric quantities**
ICNIRP Guidelines	Basic Restrictions	Reference levels
Recommendation 1999/519/EC	Basic Limits (LB)	Reference Levels (LR)
Directive 2013/35/EU	Exposure limit values (ELV)	Action Levels (AL)

The European regulations that refer directly to the ICNIRP guidelines (i.e. Recommendation 1999/519/EC [6] and Directive 2013/35/EU [7]) propose the same approach with two evaluation levels, but using a different nomenclature, which should be clarified to avoid erroneous interpretations (see Table 2).

3 - EFFECTS AND LIMITS

This section presents general aspects of the ICNIRP guidelines and the Community provisions based on them; a summary of the limit values specified by the latter is given in the Appendix.

3.1 - PROTECTION FROM THE EFFECTS OF INDUCING NAUSEA OR VERTIGO

Exposure to magnetic fields that vary very slowly over time, with a frequency lower than 1 Hz, can cause nausea or dizziness. Situations of this type occur primarily when a subject moves by translating in a non-homogeneous static magnetic field or by rotating parts of the body in a homogeneous or non-homogeneous static magnetic field.

Until the publication of the 2014 ICNIRP guidelines [5], the prevention of these effects was based solely on the limitation of the static field intensity, through specific guidelines for this physical agent [1,3]; the same approach was also adopted in Recommendation 1999/519/EC [6] – linked to the 1994 ICNIRP guidelines [1] – and in Directive 2013/35/EU [7] – which instead refers to the more recent 2009 guidelines [3].

The 2014 ICNIRP guideline, specifically designed to limit occupational exposures to very slowly varying magnetic fields, has not yet been incorporated into any legally relevant document. However, with regard to the prevention of nausea and dizziness, it specifies only a *basic restriction* consisting of **limiting the maximum variation Δ BB to 2 T.**

of the magnetic induction experienced by the exposed subject in the time span of 3 seconds.

3.2 - PROTECTION FROM THE EFFECTS OF EXCITABLE TISSUE STIMULATING

3.2.1 - General aspects

The ICNIRP guidelines for protection from the effects of **stimulation of electrically excitable tissues** have been updated, compared to the historical guidelines of 1998 [2], with the publication of the 2010 guidelines [4] (for frequencies from 1 Hz to 10 MHz) and subsequently of the 2014 guidelines [5] (for frequencies up to 1 Hz).

The latter consist of an extrapolation towards the lowest frequencies, with limit values progressively increasing as the frequency decreases, of the limits specified in the 2010 guidelines, both for the *basic restrictions* and for the *reference levels*. In the Community context, Directive 2013/35/EU takes up, with its own additions, the indications of the 2010 ICNIRP guidelines but not, up to now, those contained in the 2014 guidelines, to which therefore for the moment no formal value can be attributed, as already said; the prevention of the stimulation effects originating from movement in a magnetostatic field or from exposure to a variable magnetic field with a frequency lower than 1 Hz is therefore currently entrusted, on a legal level, to compliance with the limits provided for the static field only.

In the 2010 guidelines, the **induced electric field is used as the** *dosimetric quantity,* because it is considered the most suitable quantity to describe the stimulation effects; therefore, the *basic restrictions* are formulated in terms of internal electric field intensity. They are distinguished depending on whether one considers the transient effects that occur in the tissues of the central nervous system (CNS) of the head only (mainly in the form of perception of flashes of light called *phosphenes),* or those that give rise to the stimulation of any excitable tissue of the head or body (causing, depending on the case, tactile sensations, contractions of the skeletal muscles or interactions with cardiac function); the latter have higher onset thresholds. In the corresponding *reference levels,* the distinction between tissues of the central nervous system of the head and excitable tissues of the head and body is not adopted.

3.2.2 - Note on Community provisions

Recommendation 1999/519/EC [6] refers to the now outdated ICNIRP guidelines of 1998 [2]; in these the dosimetric quantity is the **density of electric current induced** in the tissues. Its *basic limits* are therefore formulated on the basis of this quantity, rather than of the internal electric field, and apply indiscriminately to the tissues of the central nervous system of the head and trunk.

The European Directive 2013/35/EU [7] adopts, as seen (Table 2), its own name, calling the ICNIRP *basic restrictions* **exposure limit values** and the *reference levels* **action levels.** Furthermore, it incorporates the distinction between *basic restrictions* for the central nervous system of the head only and *basic restrictions* for all tissues of the head and body, but prefers to call these limits respectively *exposure limit values relating to sensory effects* and *exposure limit values relating to health effects*. As regards the action levels, the Directive provides for **lower action levels,** corresponding to the ICNIRP *reference levels and linked to the sensory* stimulation effects and **higher action levels, linked to the** *health* stimulation effects, but with no correspondence in the ICNIRP context. Finally, for the magnetic field only, the Directive also provides for even higher *action levels,* applicable to localised exposures affecting the limbs only, also without a direct counterpart in the ICNIRP guidelines.

3.2.3 - Evaluation metrics

A very important aspect to keep in mind is that the limits relating to the prevention of stimulation effects (both the *basic restrictions* and the *reference levels)* always refer to the **instantaneous values** of the quantities involved; an excess is – at least in principle – unacceptable regardless of how brief or occasional it is. Since this assumption, if interpreted rigorously, can lead to paradoxical situations, some technical application standards introduce elements of common sense, suggesting for example to ignore transitory phenomena with a duration shorter than a certain value.

The management of spatial variability is more complex. In determining the internal electric field, to be compared with the *basic restrictions,* the value representing the 99th percentile in each tissue must be considered, but the possibility of averaging segments or millimetric volumes is also foreseen. For the comparison with the *reference levels,* the values to be considered can be the spatial maximums (certainly a precautionary choice), or the linear averages of the external electric field or magnetic field on the volume occupied by the exposed subject (but in his absence); in this second case, in the presence of fields with strong spatial gradients, it must be ensured that the basic *restrictions are respected* in the most exposed areas of the body.

3.2.4 - Fields with complex waveform

Since the safety limits specified in the guidelines vary as a function of frequency, their application is immediate only with physical quantities having a sinusoidal waveform and therefore a uniquely determined frequency.

A **complex waveform is, in this context, any** *non-sinusoidal* waveform. The frequency spectrum of a complex waveform necessarily includes at least two harmonic components at different frequencies: therefore, the problem arises of how to compare a quantity with two or more harmonic components with limit values that may be different for each of them. In this situation, the ICNIRP guidelines and other documents propose an approach that leads to the determination of an **index,** i.e. a number that integrates both the spectral characteristics of the electric field or magnetic field considered, and the variation as a function of frequency of the regulatory limit value to which one wishes to refer. The *index* assumes a value lower than 1 (or 100%, if expressed on a percentage basis) if the regulation is respected; on the contrary, if a value higher than unity is detected, we are faced with a violation. The *index* can be provided directly by the instrumentation, or it can be obtained in the laboratory, processing the results of the field measurements acquired in an appropriate way.

The two main indices used for fields with complex waveforms in relation to the stimulation effects of EMFs are the so-called **standard index** (STI) and **weighted peak index** (WPI).

The *standard index,* adopted by the ICNIRP guidelines of 1998 [2] and subsequently also taken up by those of 2010 [4], must be calculated by comparing the effective amplitude of each spectral component of the field with the respective ICNIRP *reference level* and then linearly adding all the ratios thus constructed. In formulas, assuming that we are dealing with a flux density field B, the standard index is expressed by:

$$I_{STD} = \sum_f \frac{B_{rms}(f)}{B_L(f)} \qquad (1)$$

In (1), $B_{rms}(f)$ is the effective value of the spectral component of the field at frequency *f* and *BL(f)* is the respective ICNIRP *reference level.* This setting assumes that the situation may occur in which all the spectral components of the considered waveform assume their maximum value simultaneously. The fact that this eventuality is instead quite remote is the main weakness of this approach.

The *weighted peak method,* introduced by ICNIRP in a 2003 document [10] and then taken up again in a more complete and formal way in the 2010 guidelines [4], is an alternative designed to overcome this difficulty. It requires that both the amplitudes of the spectral components of the field and their phases are taken into account. From a conceptual point of view, the following expression is used to define the weighted peak index:

$$I_{WP} = Max \left| \sum_f \frac{B_{rms}(f)}{B_L(f)} \cos[2\pi ft + \theta(f) + \phi(f)] \right| \qquad (2)$$

Operationally, once the spectrum of the waveform has been determined, the effective amplitudes $B_{rms}(f)$ of the spectral components are also related in this case to the *reference levels BL(f) at the corresponding frequencies. Furthermore, the respective phases* θ *(f)* are also considered, to each of which a further contribution ϕ *(f)* must be added, for the meaning and value of which reference is made to the ICNIRP documents; finally, it is necessary to return to the time domain and determine the absolute maximum of the synthesized waveform starting from the spectrum processed in amplitude and phase in the manner described.

3.3 - PROTECTION FROM THERMAL EFFECTS

3.3.1 - General aspects and evaluation metrics

The regulatory requirements proposed by ICNIRP for protection from the thermal effects of EMF are still those contained in the 1998 guidelines [2], which are referred to by both the European Recommendation 1999/519/EC [6] for the protection of the general population and the European Directive 2013/35/EU [7] for the protection of professionally exposed workers.

The frequency range in which thermal effects need to be considered conventionally starts from 100 kHz (see Table 1); beyond this frequency, in fact, the predominant interaction mechanism for health protection purposes consists in the absorption of energy within the human body, with a consequent increase in tissue temperature. This absorption can be conveniently evaluated in terms of **the specific absorption rate** or **SAR** (from the English *Specific Absorption Rate,* measured in watts per kilogram [W/kg]). The SAR is therefore the *dosimetric quantity* relating to thermal effects and corresponds to the power per unit of mass absorbed by the exposed subject. The accumulated scientific evidence allows us to state that **no significant thermal effects occur for SAR levels lower than 4 W/kg averaged over 6 minutes and on the entire organism;** By applying appropriate safety margins to this value, ICNIRP arrives at specifying the *basic restrictions* – differentiated for workers and the general population – both for the average SAR over the entire organism and for the local SAR in the head or limbs (averaged over 10 g volumes of contiguous tissue), in all cases always as an average over 6 minutes.

Reference levels in terms of unperturbed external electric and magnetic fields have then been identified which, if respected, guarantee compliance with these *basic restrictions*. The *reference levels must be compared with the square roots of the averages of the squares of the field intensities, taken over a 6-minute interval and over the volume occupied by the body of the exposed individual (but in his absence). In the case of highly inhomogeneous distributions, compliance with the local basic restrictions* must always be ascertained.

3.3.2 - Simultaneous exposure to multiple contributions at different frequencies

Simultaneous exposure to fields with multiple spectral components at different frequencies may occur if multiple independent sources contribute to the field levels present at the site under consideration, or when a source with a complex waveform is involved.

In the case of thermal effects, assessing compliance with the *basic restrictions* in this situation does not, in fact, pose any conceptual difficulties, since the SAR limit values are not frequency dependent: it is therefore sufficient to assess the overall SAR generated by the exposure and compare it with the relevant limit value.

With regard to *reference levels,* the ICNIRP guidelines propose an approach based on the definition of a specific **index,** through which to take into account both the spectral content of the signal considered and the variation with the frequency of the limit values with which one wishes to compare. The value of the index will indicate compliance or violation of the levels themselves, if it is respectively lower or higher than unity (or 100%, if the percentage formulation is adopted). The algorithm adopted for the calculation of this *index* takes into account the fact that the thermal effects are linked to the absorbed power (and therefore to the square of the field intensities) and are not affected by the phase relations between the various spectral components. The *index* must be calculated by comparing the square of the effective amplitude of each spectral component of the field with the square of the respective ICNIRP reference level and then adding all the ratios thus constructed. In formulas, assuming that we are dealing with an electric field E, the index for thermal effects ITERM is expressed by:

$$I_{TERM} = \sum_{f} \left[\frac{E_{rms}(f)}{E_{L}(f)} \right]^2 \quad (3)$$

In expression (3), $E_{rms}(f)$ is the effective value of the spectral component of the field at frequency *f* and *EL(f)* is the respective ICNIRP reference level.

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