Local MF transmitters find widespread use in cities, where they provide coverage on "blind spots" or other low-signal receiving areas. Powers range from 100 to 1000 W at the amplifier output and much less than that can be expected to be radiated into space. In a typical arrangement, the transmitting module is located at the top of a stucture. The radiating system is fed via a coaxial cable. It consists of a dipole over a ground plane or counterpoise laid directly on the roof. More than one transmitter can serve the same radiator. Currents can set up fields in a complicated pattern inside the building (Bini et al., 1980).

When RF fields are incident on conductive objects, RF currents are induced in the objects. Because of these currents, the objects become sources of additional fields that are highly localized and in some situations can constructively add to original fields.

Among the general population, the most popular application of microwave power is in the cooking of food. Power levels range from 300 W to 1 kW in consumer microwave models, at a frequency of 2.45 GHz. In a properly designed microwave oven, a very small fraction of this power escapes from the oven housing through various leakage paths. When leakage occurs, it is most frequently through the door seal. It may increase with use or mechanical abuse of the oven. Small amounts of leakage can also occur through the viewing screen (Osepchuk, 1979).

Personal exposure from microwave ovens is extremely small because of the rapid decrease of the power flux density with increasing distance from the oven. For worst case leakage from the microwave oven of 5 mW/cm^2, the power density at a distance of 0.3 m is less than 0.15 mW/cm^2 and, at 1 m it is about 10 μW/cm^2. Typical leakage values, therefore, imply exposure values well below the most conservative RF exposure standards in the world (Stuchly, 1977; Dumansky et al., 1980).

Recently, the induction heating stove, a new appliance for domestic use, has been introduced on the market. This appliance operates in the kilohertz range. Exposure levels at distances greater than 0.5 m are low compared with existing exposure limits, being less than 5 V/m and 0.5-10 A/m, respectively, at a distance of 0.3 m (Stuchly & Lecuyer, 1987).

Microwave anti-intrusion alarms are typical of low-power devices. These operate continuously to avoid thermal drift or switching problems, thus exposing people in the protected area. With a typical power of 10 mW, power densities of the order of 10 μW/cm^2 are measured at a distance of about 0.5 m. Population exposure to RF fields from commonly encountered sources, such as airport, marine, and police radar, is similarly very low (Stuchly, 1977; Dumansky et al., 1980, 1985b, 1988).

3.3.3 Workplace

Levels of occupational exposure vary considerably, and are strongly dependent upon the particular application. While most communication and radar workers are exposed to fields of only relatively low intensity, some can be exposed to high levels of RF. Workers climbing FM radio or TV broadcasting towers may be exposed to E fields up to 1 kV/m and H fields up to 5 A/m (Repacholi 1983a; Mild & Lovstrand, 1990).

Radar systems produce strong RF fields along the axis of the antenna. However, in most systems, average field strengths are reduced typically by a factor of 100-1000, because of antenna rotation and because the field is pulsed. With stationary antennas, which represent the worst case, peak power flux densities of 10 MW/m^2 may occur on the antenna axis up to a few metres away from the source.

In areas surrounding air traffic control radars (ATCRs), workers can be exposed to power flux densities of up to tens of W/m^2, but are normally exposed to fields in the range 0.03-0.8 W/m^2. In an exposure survey of civilian airport radar workers in Australia, it was found that, unless working on open waveguide slots, or within transmitter cabinets when high voltage arcing was occurring, personnel were, in general, not exposed to levels of radiation exceeding the specified limits in the Australian and IRPA radiofrequency exposure standards (Joyner & Bangay, 1986a).

Dielectric or RF heaters are widespread in many industries. RF energy produces heat directly within the processed material. This unique characteristic is commonly used for such purposes as sealing plastics or drying glue for joining wood. All RF heaters have a higher efficiency in comparison with conventional ovens. According to several surveys (Conover et al., 1980; Stuchly et al., 1980; Grandolfo et al., 1982; Bini et al., 1986; Joyner & Bangay, 1986b; Stuchly & Mild, 1987), the sealing or welding of polyvinyl chloride (PVC) is the most common use for RF dielectric heaters. Two pieces of plastic are compressed between electrodes and RF power is applied. The plastic material heats, partially fuses, and forms a bond. Plastic heaters frequently operate at the ISM frequency of 27.12 MHz. However, during the operating cycle, this value may vary by several megahertz. The RF output power ranges from fractions of a kilowatt to about 100 kW.

Since the exposure of heater sealer operators and other personnel working in the same area takes place in the near-field, both E and H field strengths must be measured to evaluate exposure levels. However, to demonstrate compliance with basic limits of RF exposure, the development of body current measurement techniques should prove to be useful (Allen et al., 1986). In the vicinity of RF sources, measurements of fields must be made with the operators absent from the positions that they normally occupy. The stray fields are localized in the immediate vicinity of the sealers, so that exposure of the body is highly inhomogeneous.

RF industrial heaters (plastic sealers and other devices) have been found to produce exposure fields exceeding the limits recommended in various countries and by the IRPA. Furthermore, direct current measurements have confirmed coupling of the RF energy from the device to its operator. Various methods have been developed to ameliorate the situation, such as shields, grounding strips, and others. Potential overexposure to RF radiation is probably one of the most common occurrences in the case of RF heaters, unless protective measures are employed.

Magnetic fields below a few tens of megahertz are used in industry for the induction heating of metals and semiconductors and in arc welding. Surveys of the magnetic field strength to which the operators are exposed have shown that these exposures are, in many instances, high compared with recommended exposure limits (Stuchly & Lecuyer, 1985; Conover et al., 1986; Stuchly, 1986; Andreuccetti et al., 1988; Stuchly & Lecuyer, 1989).

In many practical situations, exposure can be reduced either by administrative measures (Eriksson & Mild, 1985) or by the use of protective screening. Screening may be intentional (wire fences) or incidental (walls of buildings) and may function by reflection or by absorption. In general, both contribute to the total attenuation provided.

Thin metal sheets are adequate for the attenuation of RF electric fields. However, in many cases, it is usual to use wire screens or perforated sheets, since these have the advantages of transparency, ventilation, light weight, etc. In all cases, surveys are desirable to verify the integrity of such screens or shields. Faults in screens could, in some circumstances, be secondary sources of significant radiation or reactive fields (White, 1980).

The applications of video display units (VDUs) are numerous and their use widespread. Even more applications are anticipated in the future. In the RF region, they emit electric and magnetic fields from the cathode ray tubes (CRTs). The dominant sources are the horizontal and vertical sweep generators (fly-back transformers) operating at frequencies of some 15-35 kHz. VDUs produce fields that have complex waveforms. Typical electric field stengths at the operator position (0.5 m from the screen) range from less than 1 to 10 V/m (RMS). Magnetic flux densities range typically from less than 0.01 μT to 0.1 μT (RMS). In most VDUs, both fields are produced at the lower end of these ranges. VDUs also produce weak, electric and magnetic fields at the power line frequency (50 or 60 Hz) and its harmonics. All surveys have concluded that VDUs do not present any hazard for human health within the context of existing guidelines for exposures to non-ionizing electromagnetic fields (see section 10) (BRH, 1981; Stuchly et al., 1983b; Harvey, 1984; Repacholi, 1985; Elliott et al., 1986).

A statement has been published by the International Non-Ionizing Radiation Committee of the International Radiation Protection Association (IRPA, 1988b). Conclusions in this and other documents (WHO, 1987; ILO, 1991) are that, on the basis of current biomedical knowledge, there are no health hazards associated with radiation or fields from VDUs and that there is no scientific basis to justify radiation shielding or regular monitoring of the various radiations and fields emitted by VDUs.

3.3.4 Medical practice

Shortwave and microwave diathermy treatments are used to relieve pain through the non-invasive application of non-ionizing electromagnetic energy to body tissues. Several surveys have been published (EHD, 1980; Ruggera, 1980; Grandolfo et al., 1982; Stuchly et al., 1982; Delpizzo & Joyner, 1987), with the primary purpose of measuring the field strengths to which diathermy operators are exposed during typical treatments. Measurements of the magnitude of fields near diathermy electrodes (applicators) were made from shortwave diathermy units operating at 27.12 MHz, and from microwave diathermy units operating at 434 MHz and 2.45 GHz. They indicate emissions of high field and radiation levels in directions other than those intended for treatment. Operators, physiotherapists, and personnel performing service and maintenance tasks are exposed to stray fields and radiations. Reduction of unnecessary exposure of both operator and patient during microwave and shortwave diathermy treatments is technically achievable through adequate shielding of existing units, careful design of new equipment, and judicious planning of the treatment area (Bonkowski & Makiewicz, 1986).

Hyperthermia devices are used in cancer adjuvant therapies (Storm et al, 1981; Stuchly et al., 1983a; Hagmann et al., 1985). Treatments have been based on biological studies that suggest hyperthermia effectiveness in conjunction with radiotherapy and with chemotherapy. The evaluation of hyperthermia efficacy is proceeding through the development of therapeutic trials for specific tumours (Arcangeli et al., 1985; Perez et al., 1991). A few international and national organizations have independently determined and developed randomized trials (Lovisolo et al., 1988). For the purposes of safety evaluation, hyperthemia devices can be classified as: (*a*) those irradiating external to the body and intended for superficial and deep hyperthermia, and (*b*) those irradiating from inside the body and intended for interstitial and endocavitary hyperthermia.

All devices present, to a greater or lesser extent, problems of patient health protection. Adverse effects on patients have included pain, discomfort, burn, ulceration, and, for deep hyperthemia,

tachycardia and faintness. These are due to an overheating of superficial tissues, tissues surrounding the tumour, and, in deep hyperthermia, other tissues far from the tumour and irradiated region (Myerson et al., 1989; Petrovich et al., 1989). The magnitude of the electromagnetic field around superficial, interstitial, and endocavitary applicators is relatively low and does not cause any health risk to the operators, though the possibility of leakage of RF energy from generators and connecting cables has to be considered in some models. Capacitive and phase array devices, however, may leak RF energy (Storm et al., 1981).

Hagmann et al. (1985) measured the stray electric and magnetic fields of angular phased array and helical coil applicators for limb and torso hyperthermia at 70.93 MHz. Field strengths were measured in excess of 300 V/m and 1 A/m, respectively, at a distance of about 10 cm from the applicator. At 0.5 m, these values were reduced to 14 V/m and 0.1 A/m, respectively. In general, manufacturers of hyperthermia devices pay too little attention to minimizing the leakage of RF fields from generators, cables, and applicators, and each new model generator should be tested for RF emissions.

Magnetic resonance imaging (MRI) is now an established diagnostic technique while *in vivo* spectroscopy is undergoing rapid development. The complexity of exposure associated with MRI requires the safety consideration of three different fields (Tenforde & Budinger, 1986; Budinger, 1988). During clinical imaging, patients or volunteers, and operators are exposed to static magnetic fields, time-varying magnetic fields, and radiofrequency electromagnetic fields. RF fields in the frequency range 1-100 MHz, are deposited in patients, principally as heating associated with eddy currents induced by the RF magnetic field (Grandolfo et al, 1990). For MRI systems with static magnetic flux densities below 2 T, power deposition from electric fields associated with RF transmitter coils is relatively low, when efficient transmitter coil designs are employed. The power deposited by transient magnetic field gradients is similarly low (Bottomley et al., 1985). Staff operating the equipment are intermittently exposed to weaker fields that are present in the vicinity of the imaging equipment. Guidelines on "Protection of the patient undergoing magnetic resonance examinations" have been published by the International Non-Ionizing Radiation

Committee of the International Radiation Protection Association (IRPA, 1991).

4. EXPOSURE EVALUATION - CALCULATION AND MEASUREMENT

4.1 Introduction

Exposure evaluation provides information necessary to perform risk assessments. Two methods are available: (i) a theoretical estimation; and (ii) measurements of the fields or related parameters, such as energy absorption rates and currents.

Estimates of exposures are necessary before an installation is constructed. Whenever possible, estimates of radiation fields should be made before detailed surveys of potentially hazardous exposures are carried out. This procedure is needed to select suitable survey instruments, and to determine whether potentially hazardous exposure of the surveyor could occur, if the choice of the instrument were inappropriate or if the instrument were faulty.

4.2 Theoretical estimation

Electromagnetic waves may be harmonic, i.e., the electric and magnetic fields oscillate as sine waves, and power is generated as a continuous wave (CW) at essentially a single frequency. The waves may be also modulated, i.e., the amplitude, phase, or frequency may be changed in a chosen manner, for example, if pulse modulation, short-duration electromagnetic pulses are emitted at certain time intervals. The duration of the pulse (pulse length or pulse width), which may be of the order of small fractions of a second, is designated by t. Its reciprocal, the pulse repetition frequency (pulse repetition rate), is expressed in hertz. The product of pulse length and repetition rate is referred to as the duty cycle, D. In case of pulsed-wave generation, the emitted power increases rapidly, reaches a peak pulse power, and rapidly decreases.

This may be averaged for pulse length or per unit time, which introduces the concept of mean (average) power emitted, according to:

$$P_p = P_a/tf_r \text{ or } P_a = P_p f_r t \qquad \text{(Equation 4.1)}$$

where P_p is the peak power, P_a the average power, f_r the repetition frequency, and t the pulse length.

In practice, average power is usually measured, and, for safety purposes, mean power density is used. The peak pulse power may be many times higher than the average power output. The average and peak power flux densities (S_a and S_p) are given by:

$$S_a = DS_p \qquad \text{(Equation 4.2)}$$

Universally used sources with moveable antennas and/or beams, such as scanning or rotating radars, introduce an additional complication from the safety viewpoint. Electromagnetic power from such installations arrives intermittently.

The power flux density for a scanning antenna in motion can be estimated from the power flux density measured with the antenna stationary using the expression:

$$W_m = k_s W_s \qquad \text{(Equation 4.3)}$$

where W_m is the power flux density for the antenna in motion, k_s is the antenna rotational reduction factor, and W_s is the power flux density measured on the axis of the stationary antenna at a given distance.

In most radar installations, the antenna rotates and therefore an occupied position is exposed only when the radar beam sweeps it. The average exposure level is obtained by multiplying the measured or estimated level from a stationary antenna by the rotational reduction factor (RRF). In the far-field, RRF equals the ratio of the half power beam width to the antenna scan angle.

The rotational reduction factor (k_s) for the near-field region is equal to:

$$a/R_k \qquad \text{(Equation 4.4)}$$

where "a" is the dimension of the antenna in the scan (rotation) plane and R_k is the circumference of the antenna scan sector at the given distance r, at which the measurements have been made.

The region close to a source antenna is called the near-field. As shown in Fig.2, the near-field can be divided into two subregions: the reactive near-field region and the radiating near-field region. The

region of space surrounding the antenna in which the reactive components predominate is known as the reactive near-field region. In the radiating near-field region, the radiation pattern varies with the distance from the antenna. The near-fields often vary rapidly with distance and mathematical expressions generally contain the terms $1/r$, $1/r^2$, ..., $1/r^n$, where r is the distance from the source to the point at which the field is being determined. At greater distances from the source, the $1/r^2$, $1/r^3$, and higher-order terms are negligible compared with the $1/r$ term and the fields are called far-fields. These fields are approximately spherical waves that can, in turn, be approximated in a limited region of space by plane waves. Measurements and calculations are usually easier in far-fields than in near-fields.

When the longest dimension (L) of the source antenna is greater than the wavelength (λ), the distance from the source to the far-field is $2L^2/\lambda$. For $L < \lambda$, this distance is $\lambda/2\pi$ (see Fig. 2). In practice, the distance from the source that represents the boundary between the near-field and far-field regions is often taken to be the greater of the two quantities, λ and $2L^2/\lambda$. However, the appropriate empirical relationship depends on the type of aperture of the source and, for example, for a circular aperture, such as on a microwave relay tower, the relationship L^2/λ may be more appropriate. In this case, with a frequency of 2 GHz (λ = 15 cm), L is approximately 3 m and, consequently, the quantity L^2/λ = 60 m. Because 60 m is much greater than 15 cm, this is the distance that can be assumed as a boundary between the near- and far-field regions.

The boundary between the near-field and far-field regions, however, is not sharp, because the near-fields gradually become less as the distance from the source increases.

In free space, electromagnetic waves spread uniformly in all directions from a theoretical point source. In this case, the wavefront is spherical. As the distance from the point source increases, the area of the wavefront surface increases as a square of the distance, so that the source power is spread over a larger area.

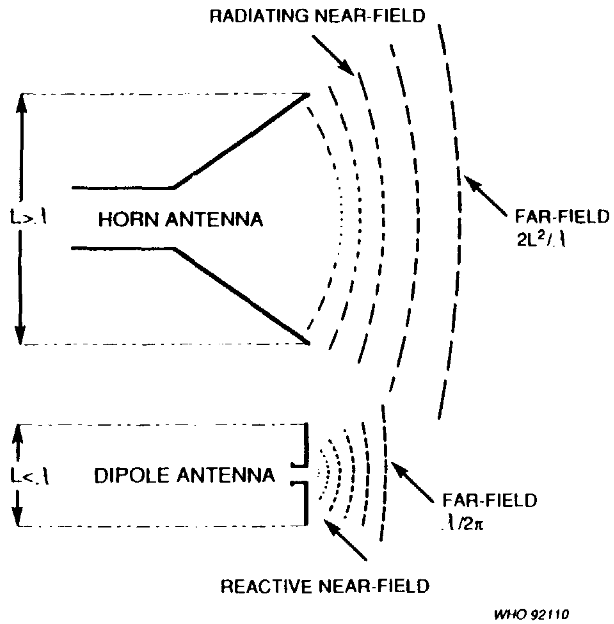


Fig. 2. Antenna size versus separation of the radiating near-field, the reactive near-field, and the far-field regions.

If the exposure takes place in the far-field of a well characterized antenna in free space, then S is calculated by the formula:

$$S = GP_t / 4\pi r^2 \text{ (W/m}^2\text{)} \qquad \text{(Equation 4.5)}$$

where G is the far-field power gain, P_t is the power transmitted (W) and r is the distance (m) from the antenna.

For a horn or reflector type antenna:

$$G = 4\pi A_e/\lambda^2 \qquad \text{(Equation 4.6)}$$

where A_e is the effective area of the antenna.

If G is not known, a useful approximation of S can be obtained by substituting the physical area A for A_e in equation 4.6. This gives a somewhat larger value for S, since A is generally larger than A_e.

Although the equations are far-field relationships, i.e., correct for distances greater than approximately $2L^2/\lambda$ ($L > \lambda$), they can be used with an acceptable error for distances greater than $0.5\ L^2/\lambda$. The error is on the safe side, since the equations predict greater values of S. However, at distances closer than $0.5\ L^2/\lambda$, the values of S predicted by the equations become unrealistically large and radiating near-field estimates must be used. For commonly encountered horn and reflector type antennas, the maximum expected radiating, near-field, power flux density S_m can be estimated (Hankin, 1974) from:

$$S_m = 4P_t/A \qquad \text{(Equation 4.7)}$$

Unfortunately, there are no equivalent reactive near-field formulae for small radiators. The radiating near-field behaviour of horn and reflector type antennas is discussed in detail elsewhere (Bickmore & Hansen, 1959; SAA, 1988). A detailed discussion of the reactive near-field of small radiators can be found in Jordan & Balmain (1968).

In the near-field, the situation is somewhat complicated, because the maxima and minima of E and H fields do not occur at the same points along the direction of propagation as they do in the the case of the far-field. In this region, the electromagnetic field structure may be highly inhomogeneous and typically, there may be substantial variations from the plane wave impedance of 377 Ω; i.e., in some regions, almost pure E-fields may exist and, in other regions, almost pure H-fields. Field strengths in the near-field are more difficult to specify, because both the E and H fields must be measured and because the field patterns are more complicated; the power density tends to vary inversely with r instead of r^2 (as in the far-field), and may display interference patterns. Near-field exposures become particularly important when considering fields from microwave diathermy equipment, RF sealers, broadcasting antennas, and microwave oscillators under test.

4.3 Measurements

4.3.1 Preliminary considerations

Several steps are necessary for the accurate assessment of RF exposure. The source and exposure situation must be characterized, so that the most appropriate measurement technique and instrumentation can be selected (ANSI, 1990; Tell, 1983). The correct use of this instrumentation requires knowledge of the quantity to be measured and the limitations of the instrument used. A knowledge of relevant exposure standards is essential.

In the following sections, information is given concerning preliminary RF survey considerations, measurement procedures, and calibration facilities.

Prior to the commencement of a survey, it is important to obtain as much information as possible about the characteristics of the RF source and the exposure situation. This information is required for the estimation of the expected field strengths and the selection of the most appropriate survey instrumentation.

Information about the RF source should include:

- frequencies present, including harmonics;
- power transmitted;
- polarization (orientation of E field);
- modulation characteristics (peak and average values);
- duty cycle, pulse width, and pulse repetition frequency;
- antenna characteristics, such as type, gain, beam width and scan rate.

Information about the exposure situation must include:

- distance from the source;

- existence of any scattering objects. Scattering by plane surfaces can enhance the E field by a factor of 2, hence, S, by a factor of 4. Even greater enhancement may result from curved surfaces, e.g., corner reflectors.

4.3.2 Near-field versus far-field

For the practical purposes of measurement, the reactive near-field exists within 0.5 λ from the source with a practical outer limit of several wavelengths (Jordan & Balmain, 1968). Both E and H field components must be measured within the reactive near-field. At present, no instruments are available commercially for the measurement of H-fields above 300 MHz, which imposes a de facto frequency limit on the measurements.

4.3.3 Instrumentation

An electric or magnetic field-measuring instrument consists of three basic parts; the probe, the leads, and the monitor. To ensure appropriate measurements, the following instrumentation characteristics are required or are desirable:

- The probe must respond to only the E field or the H field and not to both simultaneously.
- The probe must not produce significant perturbation of the field.
- The leads from the probe to the monitor must not disturb the field at the probe significantly, or couple energy from the field.
- The frequency response of the probe must cover the range of frequencies required to be measured.
- If used in the reactive near-field, the dimensions of the probe sensor should preferably be less than a quarter of a wavelength at the highest frequency present (see next section).
- The instrument should indicate the root mean square (rms) value of the measured field parameter.
- The response time of the instrument should be known. It is desirable to have a response time of about 1 second or less, so that intermittent fields are easily detected.

- The probe should be responsive to all polarization components of the field. This may be accomplished, either by inherent isotropic response, or by physical rotation of the probe through three orthogonal directions.
- Good overload protection, battery operation, portability, and rugged construction are other desirable characteristics.
- Instruments provide an indication of one or more of the following parameters:

(*a*) Average power density (W/m^2, mW/cm^2);
(*b*) Average E field (V/m) or mean square E field (V^2/m^2);
(*c*) Average H field (A/m) or mean square H field (A^2/m^2).

However, no instrument actually measures average power density and this quantity is not useful in the near-field of antennas. Power density is measured in the far-field by E-field or H-field probes. The surveyor should be aware of the field parameter (E or H) to which the instrument responds, and that exposure standards generally stipulate limits corresponding to both field parameters. Equivalent plane wave power density is certainly a convenient unit, but in the reactive near-field, E and H field components must be measured and compared with the corresponding exposure limits.

Some factors that can influence the signal levels of the instruments (e.g.,influence of multiple signals, pulse modulation, lead pick-up, coupling into probes) are discussed in detail in ANSI (1981) and Joyner (1988).

4.3.4 *Measurement procedures*

If information on the RF source and exposure situation is well defined, then a surveyor, after making estimates of the expected field strengths and selecting appropriate instruments, may proceed with the survey using a high-range probe to avoid inadvertent probe burnout and a high-range scale to avoid possible over-exposure.

In the reactive near-field of radiators operating at frequencies of less than 300 MHz, an electrically small (largest dimension $< 0.25\ \lambda$) probe sensor is required since large gradients in field components exist. Spatial resolution is critical (large probes will yield spatially

averaged values) and the use of an isotropic probe is strongly recommended. E and H field measurements should not be made closer than a distance of 20 cm from metallic objects. In some such cases, it may be possible to assess compliance with exposure standards by making contact current measurements.

Non-uniform field distributions result from reflections from various structures. Peaks in the field distribution are separated by at least one-half wavelength with the maximum levels of E and H fields occurring in different locations. Temporal variations occur also as a result of scanning antennas, scanning radiation beams, and changes in frequency. Therefore, it is imperative that any survey include a sufficiently large sample of data to preclude omission of hazardous combinations of conditions. When surveying sources of leakage radiation, such as waveguide flanges, equipment cabinet doors, and viewing or shielding screens, a "sniffing" procedure in the immediate vicinity of the equipment is required. A low-power probe and high-range setting should first be used to determine leakage sources from a distance, and lower-range settings used as a closer approach is made. Usually, leakage power varies as the inverse square of the distance.

When surveying radar antennas, it is necessary to have the antenna or the beam stationary, because the response time of the instruments is generally not short enough to indicate the maximum levels for common beam sweep and scan speed. It is important to estimate the peak exposure level, in order to ensure that the probe chosen can withstand such a peak level. Also, instruments that time-sample the field at insufficiently low sample rates should not be used for radar applications (Tell, 1983). Appropriate equations are then used to convert back to time-averaged levels for a rotating antenna.

All occupied and accessible locations should be surveyed. The operator of the equipment under test and the surveyor should be as far away as practicable from the test area. All objects normally present, which may reflect or absorb energy, must be in position. The surveyor should take precautions against RF burns and shock, particularly near high-power, low-frequency systems.

With careful measurement techniques and the correct choice of instrument, overall measurement uncertainties that are acceptable can be achieved. Direct field measurements frequently do not provide reliable means for exposure evaluation at distances from the field source (an antenna, or a re-radiating surface) of less than about 0.2 m or $\lambda/2$, whichever is smaller. In such a case, it may be necessary to evaluate the specific absorption rates (SARs) in a model of the human body using one of the dosimetric measures (Stuchly & Stuchly, 1986), or to measure directly the RF current flowing through the person (Blackwell, 1990; Tell, 1990a).

5. DOSIMETRY

5.1 General

Time-varying electric and magnetic fields induce electric fields and corresponding electric currents in biological systems exposed to these fields. The intensities and spatial distribution of induced currents and fields are dependent on various characteristics of the exposure field, the exposure geometry, and the exposed biological system. The exposure field characteristics that play a role include the type of field (electric, magnetic, or electromagnetic radiation), frequency, polarization, direction, and strength. Important characteristics of the exposed biological body system include its size, geometry, and electrical properties. The electrical properties of biological systems described by the complex permittivity and electrical conductivity differ for various tissues.

The biological responses and effects due to exposure to electromagnetic fields generally depend on the strength of induced currents and fields. However, only the external fields can be measured easily and dosimetry has been developed to correlate the induced currents and fields with the exposure conditions. Induced currents, as a measure of dose, have been used in the quantification of experimentally induced effects in animals and the results have been extrapolated to humans.

In the broad range of frequencies considered in this publication, i.e., 300 Hz-300 GHz, two different, but interrelated, quantities are commonly used in dosimetry. At lower frequencies (below approximately 100 kHz), many biological effects can be quantified in terms of the current density in tissue. Therefore, this parameter is most often used as a dosimetric quantity. At higher frequencies, where many (but not all) interactions are due to the rate of energy deposition per unit mass, the parameter specific absorption rate (SAR) is used. The SAR is defined as "the time derivative of the incremental energy, dW, absorbed by, or dissipated in, an incremental mass, dm, contained in a volume element, dV, of a given density, ρ" (NCRP 1981). The SAR is most often expressed in units of watts per kilogram (W/kg).

5.2 Low frequency range

At frequencies below approximately 0.1-1 MHz, interactions of electromagnetic fields with biological systems can be considered in terms of induced currents and their density. This approach is particularly well suited for calculations at frequencies for which the dimensions of the object are small compared with the wavelength. Under these circumstances, quasi-static approximations are valid, i.e., the effects of the electric and the magnetic field can be considered separately. The advantages of considering induced currents are twofold. First, the current densities induced in humans can be compared with those known to produce physiological responses, e.g., nerve or muscle stimulation, or they can be compared with endogenous body currents. Second, consideration of induced currents in ungrounded metallic objects can be used to assess thresholds for shocks and burns for people, who are fully or partially grounded and come in contact with such objects. Maximum current densities and the resulting maximum SARs, in some parts of the human body under certain exposure conditions, can be conveniently evaluated using the induced current approach. The direct evaluation of the internal electric fields would be much more complex and difficult. Under these conditions, limits of exposure may be expressed more appropriately in terms of induced currents rather than external field strengths.

The use of induced currents or current densities is appropriate for the assessment of acute, immediate, safety hazards, while it may have limitations for the complete evaluation of long-term effects. This has yet to be determined.

5.2.1 Magnetic fields

In accordance with Faraday's law, magnetic fields that vary in time induce the movement of electrical charge and cause potentials and circulating (eddy) currents in biological systems. These currents can be estimated using the following equation, provided that the current paths are circular:

$$J = \sigma E = 0.5\ r\sigma dB/dt \qquad \text{(Equation 5.1)}$$

where:

J = current density (A/m^2)
E = induced electric field strength (V/m)
r = radius of the loop (m) (usually several cm up to 20 cm)
σ = tissue conductivity (S/m)
dB/dt = rate of change of magnetic flux density B (T/s).

For sinusoidal fields of frequency f, equation 5.1 reduces to:

$$J = \pi r \sigma f B_0 \qquad \text{(Equation 5.2)}$$

where B_0 is the magnetic flux density peak amplitude.

The current density, internal electric field, and SAR, at any location in an exposed biological body, are inter-related as follows:

$$SAR = \sigma E^2/\rho \qquad \text{(Equation 5.3)}$$

where ρ is the physical density (kg/m^3) and

$$SAR = J^2/\sigma\rho \qquad \text{(Equation 5.4)}$$

Because of the paucity of experimental data on the biological effects of electromagnetic fields at frequencies below a few tens of megahertz, consideration of the following effects of induced current densities provides a useful alternative.

The magnitude of the magnetically induced electric fields and current densities is proportional to the radius of the induction loop in the body, to the tissue conductivity, and to the rate of change of magnetic flux density. The dependence of the induced field and current on the radius of the loop through which magnetic flux linkage occurs is an important consideration for biological systems. The induced current density is greatest at the periphery of the body, where the conducting paths are longest, whereas microscopic current loops anywhere within the body would have proportionally smaller current densities dependent on the loop size. The magnitude of the current density is influenced also by tissue electrical conductivity. In biological bodies, the exact paths of the current flow depend in a complicated way on the electrical conducting properties of the various tissues.

It is difficult to calculate the complex current distributions in biological bodies. Therefore, the treatment of this problem is restricted, at present, to relatively simplified situations.

Typical values for the low-frequency electrical conductivity are 0.1-0.35 S/m for cardiac muscle and 0.1-0.3 S/m for nerve tissue. Additionally, high ratios of transverse to longitudinal impedance up to 7:1 have been observed (Epstein & Foster, 1983).

There is very little experimental or theoretical work dealing with the coupling of magnetic fields to models of living organisms (e.g., Spiegel (1976) described magnetic field coupling with spherical models, Gandhi et al. (1984) calculated induced current densities in the torso of a human using a multidimensional lattice of impedance elements). Bernhardt (1979, 1985, 1988) performed calculations, using "worst case" assumptions, to estimate the order of magnitude for "safe" and "dangerous" values of magnetic field strengths and their frequency dependence. Considering the cardiac region and the brain as "critical" organs, approximate "worst case" calculations can be made (Bernhardt, 1979, 1985). For the purpose of these calculations, both regions can be considered as homogeneous spheres of different radii. Differences in electrical conductivity of the white and grey cerebral matter, and the anisotropic nature of conductivity at frequencies below approximately 10 kHz are not considered. A value of σ = 0.2S/m is used for the specific electrical conductivity of the cerebral substance, and a value of 0.25 S/m is used for the myocardial tissue. When a radius r of 7.5 cm of the induction loop is assumed for the head, and 6 cm for the heart, the product σr is the same for both the heart and head.

Therefore, approximately the same current densities are calculated to result in the peripheral regions of the heart and brain for a vertical magnetic field. Because of the uncertainties of the current loops and of the values for the electrical conductivities, the accuracies of these calculations are limited to about one order of magnitude. For larger effective current loops and electrical conductivities, smaller values of magnetic flux density may induce the same current densities.

The waveform is an important factor to be considered in the response of biological systems to a time-varying magnetic field. Many different waveforms of magnetic field are used in medicine and industry, including sinusoidal, square-wave, saw-tooth, and pulsed. For these fields, the parameters of key importance are the rise and decay signal times. These determine the maximum rates of change of the field (dB/dt) and the maximum instantaneous current densities induced in tissues. In order to provide an "effective" value for a variety of waveforms, root-mean-square (rms) values are often used. However, peak instantaneous field strengths appear to be important in considering nerve and muscle cell stimulation, and for perturbing cell functions. The effects depend strongly on frequency.

5.2.2 *Electric fields*

Exposure of a living organism to electric fields is normally specified by the unperturbed electric field strength. The fields that actually act on an exposed organism include electric fields acting on the outer surface of the body and electric fields and current densities induced inside the body. These fields can be different from the exposure, because of perturbations caused by placing the body in the external field. They must, however, be determined in order to specify exposure at the level of living tissues or to relate exposure levels and conditions from one species to another.

The electric fields that act directly on an exposed subject can be categorized as follows:

(*a*) *Electric fields acting on the outer surface of the body.*
These fields can cause hair to vibrate and thereby can be perceived; they may also be able to stimulate other sensory receptors in the skin.

(*b*) *Electric fields induced inside the body.*
These fields act at the cellular level, and their presence is accompanied by electric currents because of the electrically conductive nature of living tissues.

Secondary short-term effects must also be considered when evaluating health risks resulting from electric field exposure. Hazardous thresholds for some indirect effects are lower than the thresholds for biological effects due to the direct influence of electric fields. In this case, the following points are important:

- Contact currents enter a person through electrical conductors in contact with the skin.

- For static and low-frequency fields, spark discharges introduce transient currents into the body via an arc gap, when the electrical breakdown potential of air is exceeded.

- Electric or magnetic fields may interfere with the performance of unipolar cardiac pacemakers.

Therefore, a clear distinction is necessary between effects caused by the direct influence of electric fields and indirect effects caused by approaching or touching electrically charged objects, or by electromagnetic interference with implanted electromedical devices.

Within the body, the current and the current density are the two main quantities of interest. The total current is more easily measured or calculated, but the current density is more directly relevant to electric field effects in a particular tissue or organ. The electrical complexity of the interior of the human body, due to the presence of insulating membranes and tissues of various impedances, has so far frustrated confident analysis of precise interior current densities (Kaune & Phillips, 1980; Spiegel, 1981).

Electric field coupling occurs through capacitive and conductive mechanisms. A body is coupled to an electric field in proportion to its capacitance to the ground as one equipotential surface, such that the greater the capacitance the greater the current flow in the body. By definition, in capacitive coupling, the body, according to its capacitance C, "acquires" a certain amount of surface charge Q and attains a potential $V = Q/C$. The capacitance, and, thus, the induced current, decreases for a body separated from the ground and not close to an energized electrode. The capacitance is dependent on the size (especially on the surface area), the shape, and the orientation of the body. Internal currents will differ between fat and thin persons, between persons standing and reclining, and between persons walking barefoot and those wearing shoes or standing on a non-conductive platform. In all cases, it is necessary, to define the conditions under which the capacitance has been measured.

A short-circuit current, I_{sc}, flows in a body placed in an electric field and connected to the ground through a low resistance path

(paws, bare feet, a hand grasping an earthed pole). This current is the sum of all the displacement currents collected over the surface of the body. The only place on the body where a current of the magnitude of the short-circuit current flows is where there is connection with the ground. The total current induced in the body is simply the Maxwell's displacement current density multiplied by the effective area of the body. Since the body is highly conducting, this current is completely independent of the body's dielectric parameters. Deno (1977) determined this effective area by measuring the surface currents induced in hollow metal mannequins exposed to 60 Hz electric fields. He characterized the complete current distribution and determined the total short-circuit current to ground.

The equivalent area for an adult human corresponds to an effective surface area of 5.08 m^2 for a 1.77 m-tall subject. This results in a total short circuit to ground current I_{sc} (mA) for a grounded person given by:

$$I_{sc} = 0.09\, h^2 E f \qquad \text{(Equation 5.5)}$$

where h(in m) is the height of the person, E (in kV/m) is the electric field strength, and f (in kHz) is the frequency.

From measurements by Guy & Chou (1982) and Tell et al. (1982), the values of short-circuit current obtained by Deno for the metal foil models were confirmed to be the same for humans at frequencies of up to 1 MHz.

The results are shown in Fig. 3, normalized to an exposure level of 614 V/m. Since the threshold for RF burns was found by Rogers (1981) to be 200 mA, it is clear that an exposure level of 614 V/m does not protect humans against RF burns resulting from contact with grounded objects.

Deno's current distributions can be used to calculate spatial distributions of SAR as well as average SAR for real human bodies exposed to electric fields of wavelengths that are large compared with the size of the body.

To make accurate calculations of the SAR distributions from the body current distributions for various exposure conditions, it is necessary to determine the electrical conductivity and resistance per

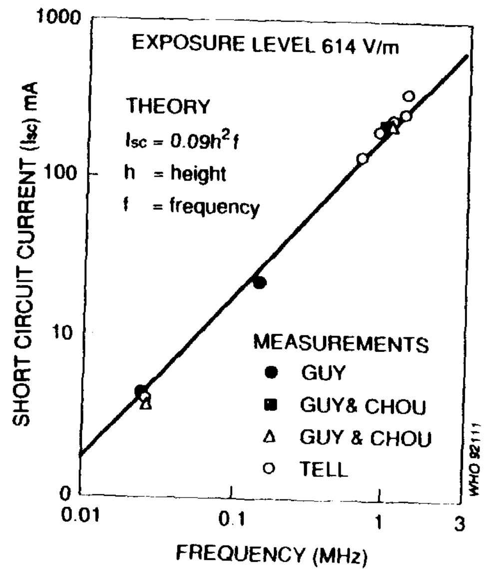


Fig. 3. Comparison of measured and calculated body-to-ground currents as a function of frequency for human subjects exposed to electric fields. From: Guy (1987).

unit length along the axis of the body and limbs. At frequencies between approximately 60 kHz and 3 MHz, this can be simply achieved by passing a known very low-level (VLF-MF) current through the whole body and measuring the potential at various points.

Calculations of SAR for exposure levels of 614 V/m, based on measured electrical conductivity and current distribution, are illustrated in Fig. 4 for exposure conditions where the feet are grounded. The maximum SAR values were obtained from the average values in each elliptical element by assuming that the current would be shunted through fat, bone, and muscle tissues, according to the ratios of the electrical conductivity of each tissue to the average electrical conductivity of the entire elliptical element.

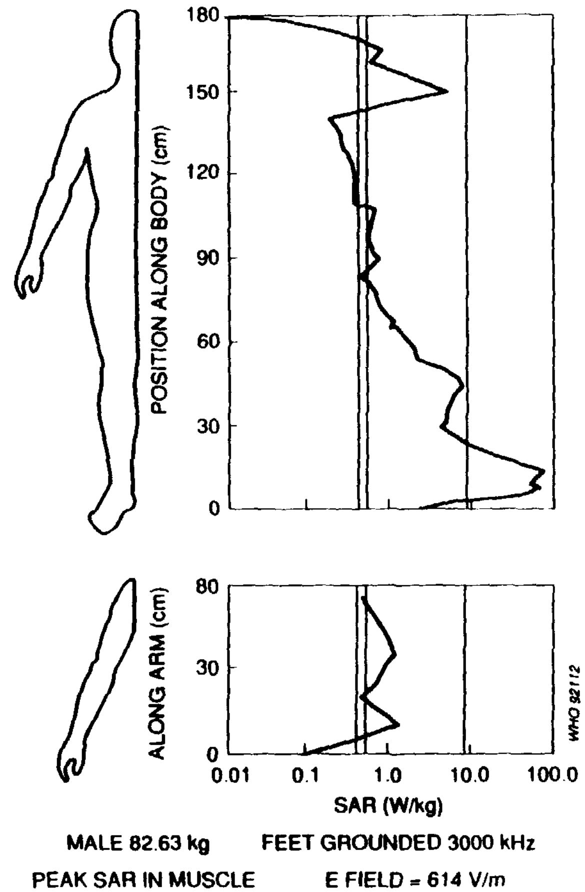


Fig. 4. The calculated peak specific absorption rate (SAR) distribution in human subjects exposed to an electric field with feet grounded. From: Guy (1987).

The peak SAR occurring in the muscle and blood vessels of the ankle, when the feet are grounded, reaches a value of 100 W/kg. Gandhi (1985) was the first to draw attention to this problem.

Although these SAR values are quite high, they occur in a relatively small volume and the thermal consequences are difficult to predict.

In studies on the distribution of the electric field or the absorbed power in different parts of the human body, it has been demonstrated that, for fields of frequencies below 10 MHz, the internal field strength increases in direct proportion to the frequency for a given external electric field strength. Therefore, a simple relationship exists between the internal and the external electric field strengths, depending on the body part or organ considered, on the electrical conductivity, and on the exposure conditions.

A detailed evaluation of current density thresholds as a function of frequency for various interactions, and an estimation of maximum current densities in models of humans exposed to electric and magnetic fields of frequencies of less than 100 kHz, have been reported (Bernhardt, 1985). Envelope curves of current densities that are required for cell stimulation, and those associated with endogenous currents in brain tissue have been established for fields of frequencies up to 100 kHz.

The current densities induced within the body by an external electric field E and frequency f were calculated using the formula $J = KfE$. The constant K depends on the part of the body considered (Bernhardt, 1985). The longitudinal axis of the body parallel to the external E field represents optimum coupling geometry and must be considered as the "worst case".

The K values can be determined by two different methods. Data from studies by different authors on absorption within the quasi-static range can be used, or K can be determined by calculating the current densities on the basis of the field strength measured on the body-surface at 50/60 Hz. The K values, determined by entirely different methods, coincide satisfactorily. The same value $K = 3.10^{-9}$ S/(Hz m) was obtained for the cardiac region and head, however for other parts of the body the values of K may be larger (Kaune & Phillips, 1980; Guy et al., 1982; Kaune & Forsythe, 1985). The surface E field and current density data derived from human measurements (Deno, 1977) and animal data (Kaune & Phillips, 1980) demonstrate that the external unperturbed fields, which are almost always used to specify exposure, must be scaled to equalize internal current densities or surface E fields. This must be done in

order to extrapolate biological data from one species to another. This process is complicated by the fact that the actual value of the scaling factor depends on the internal quantity that is being scaled.

Currents in electrically-grounded people exposed to fields at frequencies below 50 MHz have been measured (Guy & Chou, 1982; Gandhi et al., 1985b, 1986). The resulting SARs in a small volume within the ankle were estimated to be in the range of 200-540 W/kg for E fields of 61.4 V/m in the range of frequencies 40-62.5 MHz. However, lower values were found in a quantitative analysis by Dimbylow (1987, 1988).

The SAR in the wrist for contact with isolated metallic objects in an RF field has been calculated as a function of contact current for various frequencies used in broadcasting (Tell, 1990). The maximum contact currents to maintain the SARs below 8 W/kg and 20 W/kg are given in Table 5. The values in Table 5 are based on an assumed effective wrist cross section of 11.1 cm^2.

Table 5. Maximum contact currents to keep SARs in the wrist below 8 and 20 W/kg[a]

Broadcast band	Limiting current to control SAR (mA)	
	<8 W/kg	<20 W/kg
AM (0.55-1.6 MHz)	75.1	119
Low VHF (54-88 MHz)	84.1	133
FM (88-108 MHz)	87.3	138
High VHF (176-216 MHz)	93.6	148
Channel 14 (470-476 MHz)	99.7	158
Channel 20 (506-512 MHz)	100	159
Channel 66 (782-788 MHz)	124	197

[a] From: Tell (1990).

5.3 High-frequency range

The interaction of RF fields with matter can be described in terms of its electrical properties, which are the macroscopic reflection of interactions at the molecular or cellular level. The basic interaction mechanisms, which are discussed in section 6, involve relaxation phenomena due to the rotation of polar molecules, such as water, amino acids, protein, lipids, interfacial space-charge polarization due to non homogeneous structures (e.g., cell membranes), and ionic conduction.

The internal fields can be quantified in various ways. The magnetic permeability of tissue is practically equal to that of free space, and all known and anticipated interactions occur through mechanisms involving the electric field (including the current induced by the magnetic field). Therefore, the electric field vector, or its distribution throughout the exposed body, fully describes the exposure field-tissue interactions. Some additional information may be needed for full quantification, e.g., the frequency characteristics of the exposure field, such as modulation characteristics and modulation frequency.

A direct calculation of the expected temperature rise (ΔT in kelvin) in tissue exposed to RF fields for a time (t seconds) can be made from the equation:

$$\Delta T = (SAR)\, t \,/\, C \qquad \text{(Equation 5.6)}$$

where C is the specific heat capacity expressed in J/kg K. This equation, however, does not include terms to account for heat losses via processes such as thermal conduction and convection. Although it expresses the rate at which the electromagnetic energy is converted into heat through well established interaction mechanisms, it provides a valid quantitative measure of all the interaction mechanisms that are dependent on the intensity of the internal electric field in a non-linear manner. Some additional information may be relevant. For instance, since some effects of RF fields modulated in amplitude at ELF (extremely low frequencies) are dependent on the electric field intensity (Adey, 1981), they could probably be expressed in terms of the SAR, modulation characteristics, and the "zones" or windows of amplitudes of the SAR that are biologically effective.

The SAR concept has proved to be a simple and useful tool in quantifying the interactions of RF fields with living systems. It enables comparison of experimentally observed biological effects for various species under various exposure conditions and it provides the only means, however imperfect, of extrapolating animal data to potential hazards for humans exposed to RF. It also facilitates planning and effective execution of therapeutic hyperthermic treatment.

Dosimetry in bioelectromagnetic research has been developing in two parallel but interacting complementary ways, the theoretical and the experimental. RF dosimetry calculations can be performed by solving Maxwell's equations for a given configuration approximating the exposed object (an animal, a human being, a part of a human body) and for given exposure conditions (e.g., a plane wave at a given frequency, incident from a given direction). These data have been collected and discussed in the *Radiofrequency radiation dosimetry handbook* (Durney et al., 1986). However, even analyses of greatly simplified models provide valuable information for quantifying interactions of electromagnetic fields with biological systems. The results obtained from simple models often provide valuable insight and qualitative understanding that can facilitate the analysis of more complex models.

Fig. 5 illustrates the average SAR as a function of frequency for an average man exposed to a plane wave for three polarizations (Durney et al., 1978; Durney, 1980). Various models used in the calculations are also indicated.

From these data, the following conclusions can be drawn:

- the average SAR is a function of frequency;
- the average SAR depends on the wave polarization, and is greatest for the E polarization (electric field is parallel to the long axis of the body), except at higher frequencies, where it is slightly greater for the H polarization (magnetic field (H) is parallel to the long axis of the body);
- the average SARs for the E or K polarizations (when electric field (E) or wave propagation direction (K), respectively, are parallel to the long axis of the body) exhibit a maximum at certain frequencies, called the resonant frequencies.

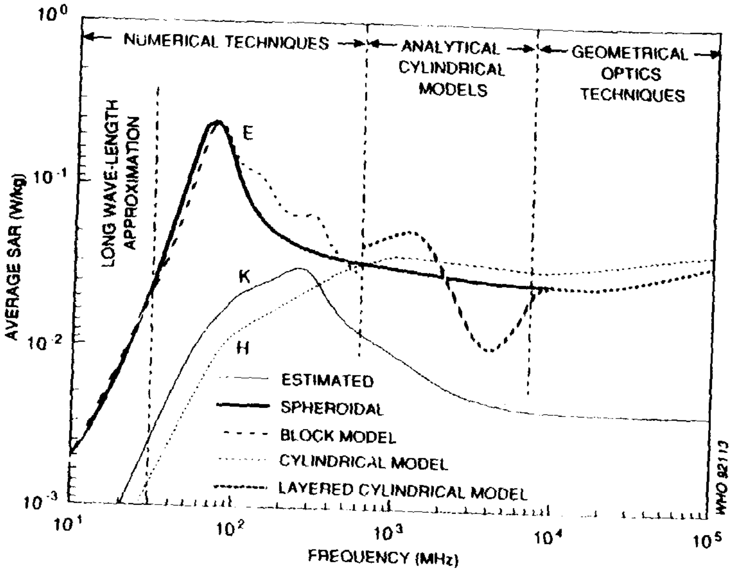


Fig. 5. Various techniques used to calculate the average SAR for models of the average man, irradiated by an EM plane wave of 10 W/m² power density. E, K, and H designate polarizations in which the incident electric field vector, propagation vector, and magnetic field vector, respectively, are parallel to the long axis of the body. From: Durney (1980).

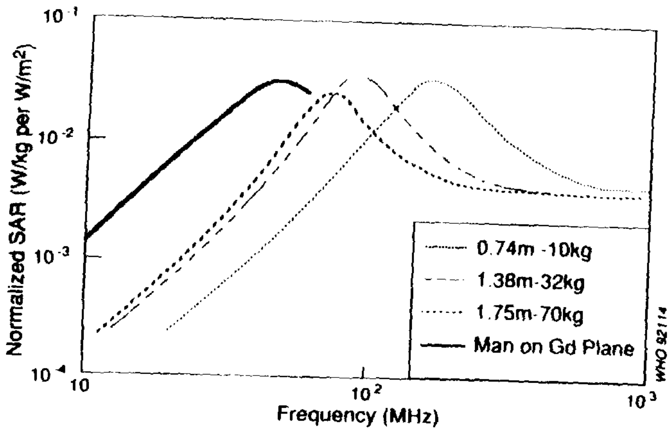


Fig. 6. Specific absorption rate for humans, according to size.

The frequency-dependent behaviour is illustrated in Fig. 6 for several human sizes. The average whole-body SAR in W/kg is plotted as a function of electromagnetic field frequency (MHz) for an incident average power density of 1 W/m².

Based on the absorption characteristics in the human body, the radiofrequency range can be subdivided into four regions (IRPA, 1988a), as shown in Fig. 7:

(*a*) The sub-resonance range, less than 30 MHz, where surface absorption dominates for the human trunk, but not for the neck and legs, and where energy absorption increases rapidly with frequency (in the neck and the legs significantly larger absorptions may occur).

(*b*) The resonance range, extending from 30 MHz to about 300 MHz for the whole body, and to even higher frequencies if partial body resonances, more particularly in the head, are considered.

(*c*) The "hot-spot" range, extending from about 400 MHz up to about 3 GHz, where significant localized energy absorption can be expected at incident power densities of about 100 W/m²; energy absorption decreases when frequency increases and the sizes of hot spots range from several cm at 915 MHz to about 1 cm at 3 GHz.

(*d*) The surface absorption range, greater than about 3 GHz, where the temperature elevation is localized and restricted to the surface of the body.

The average SAR varies with species, as illustrated in Fig. 8. These data are of importance in extrapolation of the results from experimental animal studies to human exposures. The average SAR varies within one order of magnitude in the subresonance range, depending on the separation of an average person from the electric ground plane (with the highest SAR for a person on a ground plane).

Whole-body-average SARs have been measured for humans (Hill, 1984a,b,c; Hill & Walsh, 1985), and the spatial distribution of the SARs in full-scale, realistic models of the human body (Kraszewski et al., 1984; Stuchly M. et al., 1985, 1986; Stuchly S. et al., 1985). The whole-body average SAR was measured for human volunteers

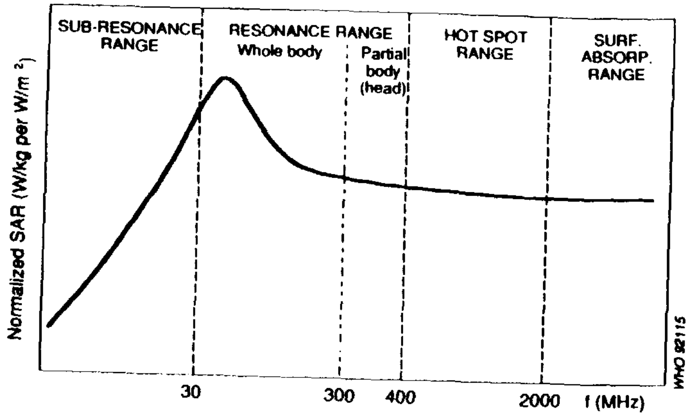


Fig. 7. Variation of normalized SAR with frequency and related absorption characteristics in living organisms.

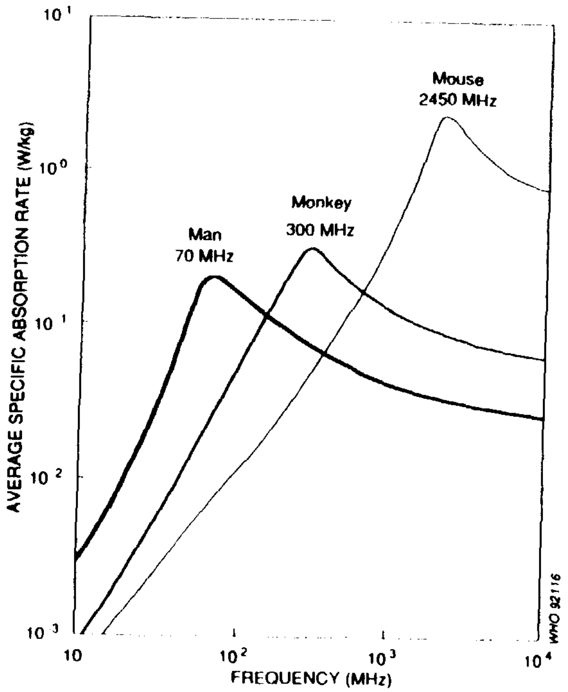


Fig. 8. Average SAR for 3 species exposed to 10 W/m^2 with the E vector parallel to the long axis of the body. From: Durney et al. (1978).

exposed to RF at a few frequencies between 3 and 41 MHz, which are below and close to the resonant frequencies of adult humans. The exposure conditions simulated free-space and grounded conditions in the orientation that results in the greatest SARs (Hill, 1984a, b, c). At all frequencies, the measured SARs exceeded the calculated values by a factor of 2.7-3.9 in free space, and 4.3-4.4 for the grounded condition.

Similar differences between the calculated and measured SAR for simple models were found on scaled-down models at 5-10 MHz (Guy, 1987). Spatial distributions of the SAR in models of the human body have been investigated experimentally (Guy et al., 1984; Kraszewski et al., 1984; Stuchly M. et al., 1986; Stuchly S. et al., 1987). Large differences, typically by a factor of 10-30, between the measured SAR values and those previously calculated using a block model, have been observed (Stuchly M. et al., 1986) at frequencies above resonance. However, despite the differences in spatial distributions, the ratios of peak to whole-body average SARs predicted theoretically and measured, were relatively small, except for the SAR at the body surface. With reference to developing human exposure limits, these results underscore the limitations of the theoretical methods of prediction available at present.

The measurements on a full-scale model (Olsen, 1982; Stuchly S. et al., 1986), on a scaled-down model of man (Guy et al., 1984), and on a full-scale model of a monkey (Olsen & Griner, 1982) all indicated that, for free space and the most absorbing orientation (E-polarization), measured values are close to those predicted from calculations at, and above, the resonant frequency (up to about 450 MHz).

Changes to the average SAR for important practical exposure conditions (e.g., separation between the subject's feet and the ground plane, the body position, articulations of the limbs, and two-body interactions) have been investigated using human volunteers (Hill, 1984b, 1984c). Footwear reduces the average SAR with the degree of reduction depending on the type of footwear and the frequency of the exposure field.

Similar effects have been observed in body currents measured in people exposed to HF and VHF antennas (Allen et al., 1988).

Similar effects have been observed in body currents measured in people exposed to HF and VHF antennas (Allen et al., 1988).

High local SARs also occur at frequencies around and below the resonant frequency at locations such as the ankles (Gandhi et al., 1985b, 1986) and the wrist (Guy & Chou, 1982). At frequencies above a few GHz (millimetre waves), high local SARs are produced at the body surface (Gandhi & Riazi, 1986). Exposures corresponding to 10 W/m^2 may result in perception of heating.

Data have also been collected on the SAR distribution for near-field exposures (Stuchly M. et al., 1985, 1986, 1987; Stuchly S. et al., 1985, 1986). One of the most important findings is that the SAR distributions are highly non-uniform, with typical ratios between spatial peak and whole-body average SARs of the order of 150:1 to 200:1 (Stuchly S. et al., 1985). At all frequencies investigated, the maximum SAR is at the body surface, with lower magnitude "hot spots" located inside the body. Practically all the energy, however, is deposited within about 20% of the body volume closest to the antenna. Knowledge of these SARs can be used in specifying, for instance, the maximum output power of portable transmitters that would be allowed under a selected limit of the SAR.

5.4 Derivation of exposure limits from basic quantities

For the assessment of the possible health effects of electromagnetic fields, it is useful to differentiate between basic limits and derived limits.

Basic limits may be directly correlated with biological effects. Using experimental data or related studies, a threshold exposure level can be determined, above which adverse health effects are increasingly likely, but below which no adverse effect occurs. The basic exposure limit is based on this threshold level.

Since basic limits in terms of SAR or induced current density cannot be measured easily in practical exposure situations, exposure limits in conveniently measured quantities are derived from the basic limit. These derived limits then indicate the acceptable limits in terms of measured and/or calculated field parameters.

Three categories of basic limits have been identified and quantitatively established.

1. The specific absorption rate (SAR) averaged over the whole body or over parts of the body:
   Whole body SAR is a widely accepted measure for relating adverse effects to RF exposure, especially for frequencies above about 10 MHz. Local SAR values are necessary to evaluate and limit excessive energy deposition in small parts of the body and to avoid hot spots resulting from special exposure conditions. Examples of such conditions are: a grounded individual exposed to RF in the low MHz-range; individuals exposed in the near-field of an antenna or individuals exposed at the higher end of the frequency range, where the penetration depth of the RF is low.

2. The induced electric field strength or current density:
   RF fields can induce sufficiently high current densities to stimulate excitable tissue (nerve or muscle) or to produce other potentially harmful effects, especially at frequencies below 100 kHz. The thresholds for biological effects are expressed in terms of current density and are strongly frequency dependent.

3. Contact current between a person and a charged object:
   A conductive object in an electric field can be energized by the field. For field frequencies below 100 kHz, contact between the object and a person may result in stimulation of electrically excitable tissue with pain and more severe effects (burns), if the current density is sufficiently high. For frequencies between about 100 kHz and 100 MHz, the hazard of burns from contact current will predominate.

Derived limits are necessary to provide a practical method to evaluate a given RF exposure. Derived limits obtained from one of these basic limits above include, e.g., electric and magnetic field strength, power density, contact voltage of the conductive objects, and short-circuit currents. The derived limits have to be calculated in such a way that, even under worst-case conditions of field exposure, the basic limits will not be exceeded. In many special exposure conditions, e.g., in the near-field, very close (less than 0.5 wavelength) to an antenna, the assessment of possible health effects may require separate measurements or calculations to investigate whether the basic limit is exceeded.

6. INTERACTION MECHANISMS

6.1 General

Electromagnetic fields in the frequency range 300 Hz-300 GHz interact with biological systems (humans and other animals) through direct and indirect mechanisms. A direct interaction produces effects in the exposed organisms directly from exposure to the electromagnetic field. An indirect interaction is mediated through the presence of other bodies in the electromagnetic field, and occurs as a result of an interaction (usually physical contact) between the biological body and another object, such as an automobile, fence, or even another biological body.

Direct interactions that are well understood can be quantified in terms of dosimetry, and can be considered as resulting from induced currents and internal electric fields. The macroscopic spatial distribution of these currents and fields within an exposed biological body is of importance and is determined by theoretical and experimental dosimetry. The spatial distributions of the currents and fields within, and around, the cell are also important. As outlined earlier, the patterns of induced currents and fields within biological systems usually are highly non-uniform and depend on the geometry and electrical properties of the exposed system, as well as on the field frequency, and, for lower frequencies, the type of field, whether electric or magnetic (where spatial separation of the electric and the magnetic field is realistic). The extent to which the electric or magnetic field plays a role is uncertain. However, apart from differences due to different current distributions, the frequency of the field clearly establishes the type of mechanism for the mechanisms that are well understood.

For frequencies below about 100 kHz, an established interaction mechanism is the stimulation of excitable tissues by induced currents. For higher frequencies, thermal interactions predominate. At the lower frequencies, much less of the electromagnetic field is absorbed by biological systems. Thermal interactions occur at energy levels much higher than interactions due to induced currents. Therefore, thermal interactions are usually of little interest for fields at levels at which people are exposed. Additionally, at frequencies below approximately 1 kHz and at higher frequencies amplitude modulated at extremely low frequencies (1-300 Hz), there is experimental

evidence that interactions occur through mechanisms other than thermal or cell excitation. These mechanisms are not understood.

In the context of direct and indirect interaction mechanisms, the electrical properties of tissues have to be considered. Macroscopic electrical properties of tissues play a major role in defining induced currents and fields and their patterns inside the body. Microscopic electrical properties provide an insight into events at the molecular and cellular level that result from exposure of the biological body to an electromagnetic field.

A brief review of tissue electrical properties is presented in this section, together with a discussion of direct and indirect interaction mechanisms.

6.2 Electrical properties of cells and tissues

6.2.1 *Permittivity*

The interactions of an electric field with matter are described in terms of the complex permittivity, ϵ^*:

$$\epsilon^* = \epsilon' - j\epsilon'' \qquad \text{(Equation 6.1)}$$

where ϵ' is the dielectric constant, ϵ'' is the loss factor, and $j = \sqrt{-1}$.

Equation 6.1 is a representation in the complex plane of a physical property, in this case the permittivity. Such representation indicates two distinct properties. The dielectric constant, ϵ', is a measure of the ability to store electric field energy. The loss factor, ϵ'', describes a fraction of energy dissipated in the material per cycle.

The permittivity represents a combined macroscopic effect of various molecular phenomena causing electrical polarization. It includes contributions from relaxation phenomena due to molecules, cells, and ion layers surrounding molecules. For convenience, it also includes the contribution from ionic conductivity (movement of ions). The contribution of each of the phenomena varies with frequency.

Frequently, the relative permittivity is used, i.e., the permittivity normalized to that of free space (vacuum):

$$\epsilon^*_r = \epsilon'_r - j\epsilon''_r = \epsilon^*/\epsilon_0 = \epsilon'/\epsilon_0 - j\epsilon''/\epsilon_0 \qquad \text{(Equation 6.2)}$$

where ϵ_0 is the permittivity of free space, 8.85×10^{-12} F/m.

The loss factor, ϵ''_r, is related to the electrical conductivity of the material, σ, in the following way:

$$\epsilon''_r = \sigma/\omega\epsilon_0 \qquad \text{(Equation 6.3)}$$

where $\omega = 2\pi f$, f is the frequency. The unit of electrical conductivity is siemens per metre (S/m). The electrical conductivity consists of two terms, the static electrical conductivity due to ionic conduction, and the electrical conductivity due to various polarizabilities.

Electrical properties of tissues change over a few orders of magnitude with frequency in the range as shown in Fig. 9 (note the logarithmic scale).

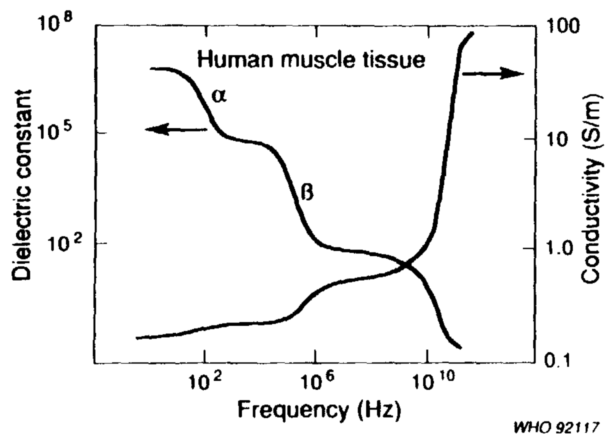


Fig. 9. The dielectric constant and conductivity of typical biological tissue as functions of frequency. From: Schwan (1985).

Biological tissues exhibit three strong relaxation phenomena (the α-, β-, and γ-dispersion) and one weak (the δ-dispersion) (Foster & Schwan, 1986, 1989). The molecular phenomena responsible for the α-dispersion are the least understood.

Relaxation of counter-ions about the charged cellular structure, intracellular structures, e.g., the tubular apparatus in muscle cells, relaxational behaviour of membranes themselves, may all contribute to this dispersion to various degrees. The β-dispersion is mostly due to membranes, which separate regions having different dielectric constants and electrical conductivities, resulting in an interfacial polarization causing the Maxwell-Wagner type relaxation. Smaller contributions result from the relaxation of proteins. The γ-dispersion is due to free water relaxation and the δ-dispersion results from relaxation of bound water, amino acid, and charged side groups of proteins.

The α-dispersion occurs at frequencies that are usually below 10 kHz, the β-dispersion at about 20 kHz-100 MHz, the δ-dispersion at 100-1000 MHz, and the γ-dispersion at 25 GHz (at 37 °C).

All the dispersions in most tissues occur over a broad range of frequency, because of the highly non-uniform structure of tissues, and usually with more than one specific interaction mechanism contributing to the dispersion (Foster & Schwan, 1986, 1989; Stuchly & Stuchly, 1990).

The permittivity of cells and tissues has been extensively studied and comprehensive reviews can be found (Foster & Schwan, 1986, 1989; Stuchly & Stuchly, 1990). A detailed description on the molecular/cellular level of all the relaxation phenomena is provided in a review by Foster & Schwan (1989).

Resonant dielectric absorption was reported in DNA solutions at 1-10 GHz (Edwards et al., 1984, 1985). Various theoretical hypotheses were proposed to explain the resonances (Scott, 1985; Van Zandt, 1986). However, more careful measurements were performed by three other research teams (Foster et al., 1987; Gabriel et al., 1987; Maleev et al., 1987) and a part of the original team that found the resonance (Rhee et al., 1988). None of the groups found resonant behaviour of DNA in aqueous solutions. A lack of resonant behaviour is in agreement with the earlier experimental data on the dielectric properties of DNA (Takashima et al., 1984).

6.2.2 Non-linear effects

The bulk dielectric properties of tissues reflect the passive properties of cells, e.g., the capacitance of cell membranes (Foster & Schwan, 1989). The physiological response of the membrane to the changes in the membrane potential, due to the applied field, results in nonlinearity. These phenomena include changes in the membrane conductance associated with gating and action potentials. An induced potential across the membrane of the order of 10 mV or more is required to produce firing of a resting nerve cell, which for a membrane thickness of, for example, 50 nm corresponds to an electric field strength of 200 kV/m. However, substantially lower electric field strengths can induce changes in the firing pattern of pacemaker cells (Sheppard et al., 1980; Wachtel, 1985). At high field strengths (voltages across the membrane), pores are formed in the membrane, and, eventually, at a few hundred mV across the membrane, breakdown occurs (Foster & Schwan, 1989).

Muscle cells exhibit an anisotropic excitation, which is consistent with the following phenomenon. The maximum voltage across the membrane for spherical cells is related to the electric field strength by the following relationship (Foster & Schwan, 1989):

$$V_m = 1.5\ rE \qquad \text{(Equation 6.4)}$$

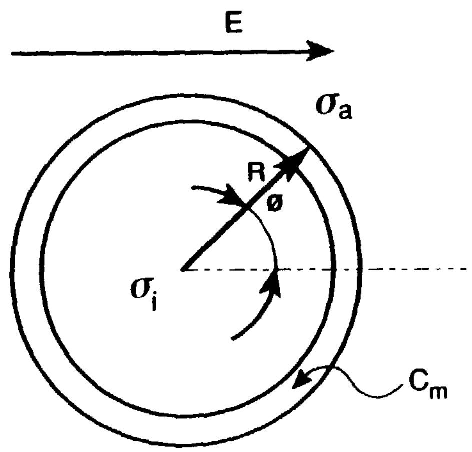
where r is the cell radius, and E is the electric field strength in extracellular fluid (Fig. 10). For ellipsoidal cells, similar equations have been derived by Bernhardt & Pauly (1973). Their results show that electric fields axial to a cell induce a voltage across the membrane that is proportional to the length of the cell and to the extracellular electric field strength. Thus, asymmetrical muscle cells exhibit dimension-dependent induced voltages, when exposed to electric fields.

Gradients in the induced surface charge can also affect molecules and cells in solution. Polar molecules (e.g., water, proteins) align themselves with the field at high electric field strengths of the order of 10^6 V/m. Also, non-spherical cells align themselves with the field and form "pearl chains". The larger the cell, the lower the field strength required for orientation and formation of pearl chains. For instance, for a cell of radius 1 μm, an electric field of 10 kV/m is required (Foster & Schwan, 1989).

Counter-ion polarization is likely to produce a nonlinear dielectric response at moderate field strengths of the order of a few hundred V/m in tissue for large cells, but the response is slow to develop, and the relaxation frequency is a fraction of a hertz. There have been relatively few studies on the nonlinear responses of the counter-ion relaxation (Foster & Schwan, 1989).

6.2.3 Induced fields at the cellular level

Knowledge of the electric fields acting on specific parts of the cell due to a certain electric field in tissue is important in predicting cell stimulation. It is also important to evaluate the possibility of interaction with the genetic apparatus, when fields of sufficient strength are acting at the cell nucleus. A general analysis of these fields was performed by Schwan (1984) and Foster & Schwan (1989). The results of the analysis are illustrated in Fig. 11 showing the plasma-membrane potential, the cytoplasm field strength, and the nuclear membrane potential, as a function of frequency.



WHO 92118

Fig. 10. A spherical cell in an electric field.

Data shown in Fig. 11 can be summarized as follows: below the β-dispersion for the cells, the plasma membrane shields the interior of the cells; above the β-frequencies for the plasma membrane and the nucleus, the induced voltage drop across both membranes falls off as the inverse of the frequency. The greatest potential is induced on the nuclear membrane at frequencies between the β-dispersion frequencies for the plasma and the nuclear membranes, and this potential is approximately equal to the product of the external electric field and the nuclear radius (Foster & Schwan, 1989). Table 6 gives a summary of induced fields in various parts of the cell and Fig. 11 gives the induced membrane potentials and electric fields in various compartments (Schwan, 1985).

Table 6. Summary of the coupling properties of external fields to cellular membranes and compartments. f_r is the beta dispersion frequency of the plasma cell membrane, where f_n is the beta dispersion frequency of the nucleus and other organelles. Approximate values of relaxation frequencies are given in brackets. [a]

	$f < f_r$ (approx 1 MHz)	$f_r < f < f_n$	$f > f_n$ (approx 10 MHz)
Cell:			
Membranes	Polarized	Not polarized	Not polarized
Interior	Doubly shielded	Shielded	Exposed
Organelles:			
Membranes	Not polarized	Partially polarized	Not polarized
Interior (Nucleic acids)	Doubly shielded	Shielded	Exposed
Connecting organelles:			
Membranes	Polarized	Not polarized	Not polarized
Interior	Not exposed	Exposed	Exposed

[a] From: Schwan (1985).

6.2.4 *Body impedance*

To determine the currents that flow when a person in an electromagnetic field comes into contact or close proximity with an isolated conducting object, it is important to consider the impedance

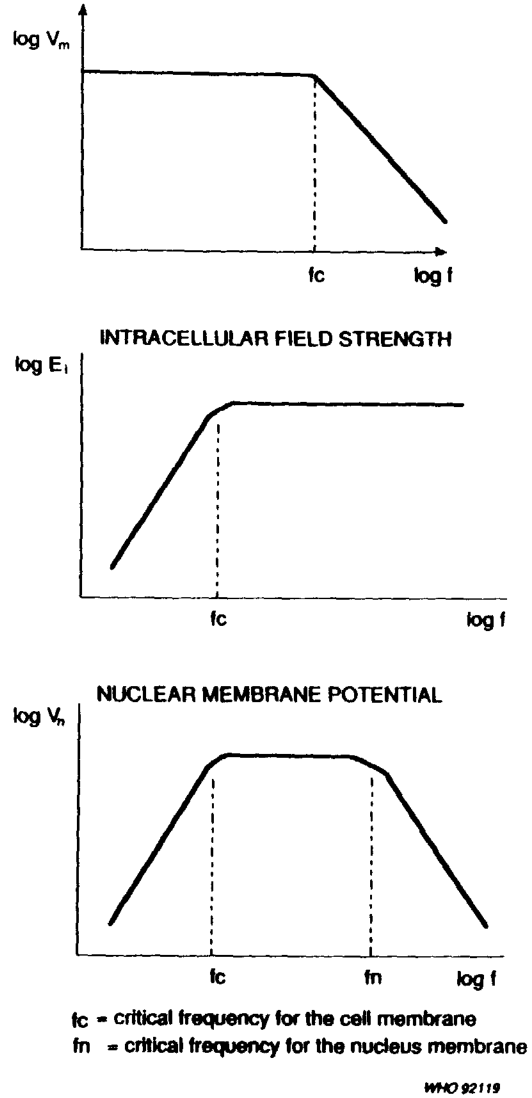


Fig. 11. Induced membrane potentials and electric fields in various cell compartments. From: Schwan (1985).

of the human body. The human body impedance can be considered as a composite of the impedances of various parts through which the current is flowing. For instance, for a finger contact with an automobile and a current flowing to ground, the total impedance is the sum of the following: the contact impedance, the finger impedance, the arm impedance, the body (trunk plus legs) impedance and the capacitance to ground. All these impedances are frequency dependent. Furthermore the contact impedance depends on the surface area and condition (dry or wet) of the contact surface, and at least at low frequencies probably on contact voltage as documented by measurements at 60 Hz (Tenforde & Kaune, 1987).

The complete body impedance can be represented by an equivalent circuit consisting of a number of resistive and capacitive components, some of them frequency dependent. Measurements of body impedance have been performed at 60 Hz (Tenforde & Kaune, 1987) and from 10 kHz to 3 MHz (Gandhi et al., 1985a).

6.3 Direct interactions - strong fields

Well established interaction mechanisms for the direct effects of electric and magnetic fields can be divided into two types, each dependent on the field frequency. For frequencies below approximately 100 kHz, the interactions (stimulation) with excitable tissue are of primary interest. Above about 100 kHz, the current density thresholds for stimulation and other effects due to interactions with excitable tissue are higher than those required to produce energy deposition rates of about 1 W/kg. At such rates of energy deposition in tissue, thermal interactions become important. In both frequency ranges, other forms of interactions are also observed for induced currents and fields below those associated with stimulation or heating.

6.3.1 Interactions with excitable tissues

In tissues, the induced electric fields are amplified across the cell membranes. At sufficiently high field strengths, these affect the electrical excitability of nerve and muscle cells. This inter-action occurs up to hundreds of kilohertz (Lacourse et al., 1985), but increasingly stronger fields are required above the β-dispersion. Changes in the membrane potential cause changes in the permeability to ions, conformational changes in the embedded proteins, a number of ion gates open, and eventually membrane depolarization results in an action potential. Threshold current densities for subtle modulations of excitable cells, and their biological significance, are less well understood. There is a substantial amount of data on tissue

stimulation, extra-systole elicitation, and ventricular fibrillation. These data, as summarized by Bernhardt (1985, 1986, 1988), are shown in Fig. 12. The ventricular fibrillation thresholds are above those needed for stimulation. Thresholds for the stimulation of excitable tissue depend not only on the current density and frequency, but also on the waveform. In the case of pulsed fields, they depend on pulse duration and other parameters (Reilly, 1988).

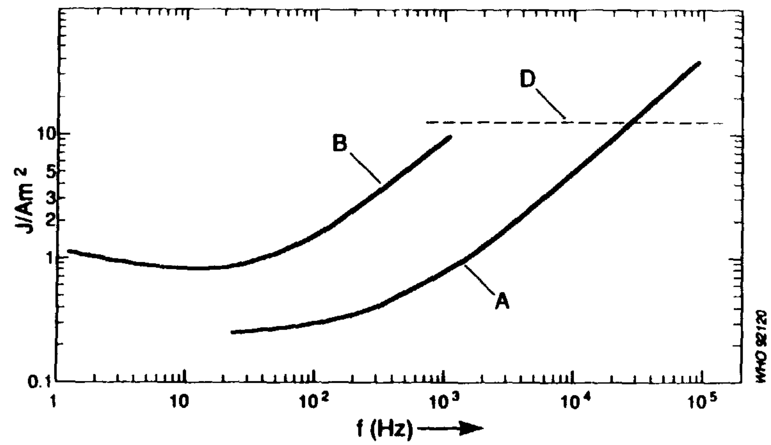


Fig. 12. Threshold current densities for effects on excitable cells. Curve A - envelope of thresholds for stimulation of various cells under various conditions; curve B - threshold for stimulation of extra-systole; and curve D - the current density approximately corresponding to SAR = 1 W/kg, in muscle tissue. Modified from: Bernhardt (1985, 1986).

6.3.2 Thermal interactions

As described in section 5, exposure to an electromagnetic field can result in a spatially nonuniform SAR in the body. The initial rate of temperature increase, when heat losses are neglected, is directly proportional to the SAR:

$$dT/dt = SAR/C \qquad \text{(Equation 6.5)}$$

where T is the temperature, t is time, and C is the specific heat capacity of tissue.

At the molecular level, the phenomena involved in a conversion of RF energy into thermal energy are the relaxation processes described earlier. Deposition of RF energy in the body may not necessarily lead to a proportional increase in its temperature, because of thermoregulatory responses. Various mathematical models for human thermoregulation have been applied to evaluate thermal interactions of RF energy (Emery et al., 1976; Spiegel et al., 1980; Way et al., 1981; Spiegel, 1982).

The rapid rate at which heating can occur, and a uniquely non-uniform spatial pattern of energy deposition are important and unique to thermal interactions of electromagnetic energy. The rate of initial heating appears to be very important for pulsed fields. These two features make biological responses due to electromagnetic thermal loading unlike those due to other thermal agents. Thermal interactions are not necessarily accompanied by significant local or whole-body temperature increases.

In some thermal interactions, biological responses depend on the temperature-time profile, where such a profile is achieved by RF heating. In some other biological responses, the rate of temperature change is the critical parameter while the total temperature rise may be very small. Here again, RF energy (pulsed) can be very effective.

One of the most prominent, thermally-induced effects, where the temperature increases are very small, is the microwave hearing effect (Guy et al., 1975a; Lin, 1978). Exposure to one pulse of electromagnetic energy results in the perception of a click, and exposure to repeated pulses in a buzzing or hissing sound. The energy threshold for human beings is very low (16 mJ/kg) and the resulting temperature increase is estimated to be only about 5×10^{-6} °C (Guy et al., 1975a). The simplified mechanism of interaction is as follows: absorption of electromagnetic energy causes a rapid temperature increase, which, in turn, produces thermal expansion pressure initiating an acoustic wave that is detected by cochlea (Guy et al., 1975a; Lin, 1978).

6.4 Direct interactions - weak fields

6.4.1 General

There is a growing body of data from studies indicating that extremely low frequency fields (ELF) (Tenforde & Kaune, 1987; WHO, 1987) and RF amplitude modulated at ELF (Adey, 1981, 1988) interact with various biological systems at energy levels significantly lower than those needed for the stimulation of excitable tissues or for thermal interactions. The mechanisms of these interactions are not understood. Several mechanisms have been hypothesized, but these need further development and testing, and possibly still other considerations need to be taken into account to unravel the rather complex mechanisms behind the observed interactions.

Pericellular currents induced by electromagnetic fields produce electrochemical alterations in components of the cell membrane surface. These changes are hypothesized to cause signals across the cell membrane and produce intracellular alterations (Adey, 1981, 1988; Tenforde & Kaune, 1987).

Weak field interactions are sometimes criticized and dismissed on the grounds that the field intensities induced in the biological systems that produce them are lower than those associated with thermal noise. A recent analysis of noise and electric fields induced on a simple model of cell membranes by Weaver & Astumian (1990) indicates that induced fields of the order of 0.1-0.01 V/m are theoretically detectable above the broad band noise level. Much smaller fields, of the order of 10^{-4} V/m, are estimated to be detectable if only a narrow frequency band response of the membrane or signal averaging are assumed. The assumption of the narrow frequency band response is consistent with some experimental data on biological responses. The signal averaging is also supported by experimental work on enzyme-catalysed reactions.

A description of some hypothetical interaction mechanisms for ELF fields, which possibly also applies to the lower frequencies of concern here (probably below 1000 Hz) and to RF fields modulated at ELF can be found in Tenforde & Kaune (1987) and WHO (1987).

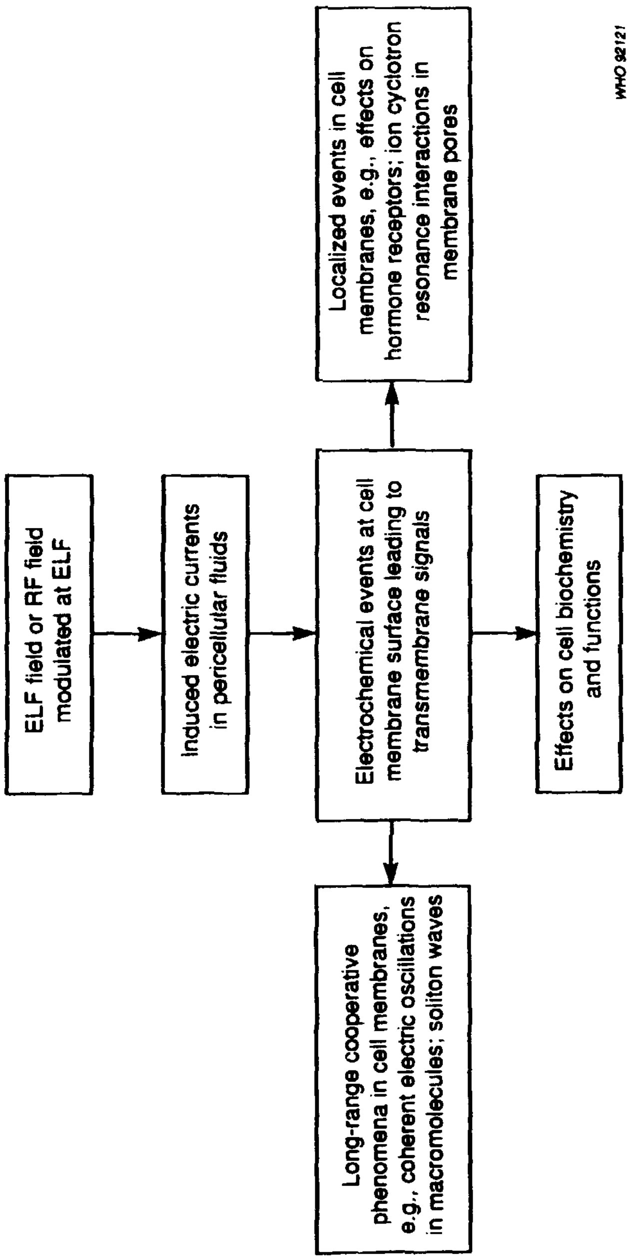


Fig. 13. Hypothetical interaction mechanisms of ELF fields or RF fields modulated at ELF. Modified from: Tenforde & Kaune (1987).

The hypothesized scheme of transductive coupling between induced electric currents in the extracellular medium and the intracellular events occurring in living cells is illustrated schematically in Fig. 13.

An alternative model involving magnetic-field induced changes in specific molecular species associated with the plasma membrane has been proposed by Blackman et al. (1988). In this model, as in others, an amplification step must be involved. Conditions for the cellular response may involve the induction of a weak electric field in the extracellular fluid, a molecular change in the membranes to "trigger" cooperative events within the cell membrane. The basic premise is that the cell membrane exists in a metastable, non-equilibrium state that can be significantly perturbed by weak stimuli. The stored energy is released by this process as metabolic chemical energy through the activation of ion pumps or enzymatic reactions within the membrane (Fröhlich, 1968, 1977; Adey, 1981, 1983). This general model may also be applicable to the results observed at 41 GHz (Grundler & Keilmann 1983, 1989). In this case, yeast growth rates have been affected at SARs as low as 0.2 W/kg.

6.4.2 *Microelectrophoretic motion*

Recent experimental evidence has given some support to the concept that the interactions of ELF fields with living cells occur at specific loci on the cell membrane. A model of membrane interactions in which a microelectrophoretic motion induced in the cell membrane by weak ELF electric fields influences the average distance between charged ligands and the cell-surface receptors to which they are bound was proposed by Chiabrera et al. (1984). In this theoretical model, the effect of the imposed electric field is to decrease the mean lifetime of the ligand-receptor complexes on the membrane surface. The authors proposed that this effect could influence various biological phenomena, such as the activation of lymphocytes by antigens and various lectins, and the gating mechanisms that control the membrane transport of various types of cations, such as calcium.

6.4.3 *Ion-resonance conditions*

Some experimental evidence suggests that effects occur at specific frequencies for ELF fields and static magnetic fields with strengths