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Effects of RF radiation on people

The nature of potential hazards

A great deal has been written over the last thirty years or more about the hazards of RF radiation. The vast majority has been in the form of serious contributions and includes a large number of research papers. Lack of accurate methods of measuring fields obviously affected some of the work of the earliest workers. As technology has improved and field measurements can now be made more accurately, the experimental methods have improved.

The problems of research in this field are fairly obvious – very few tests can be carried out on human beings. As a result, most practical work has been done on small animals such as rats, mice, rabbits, bacteria, yeast cells, fruit flies and similar subjects. There is then the problem of the extrapolation of the results to human beings when some fundamental factors, e.g. the physical sizes, and thus the resonant frequencies of the various subjects are so markedly different. Also, where thermal effects are involved, the differences in the thermo-regulatory systems of the test subjects pose a very considerable problem. Hence such extrapolation is likely to be dangerous.

An even greater problem is the fact that the radio frequency spectrum is so very wide (perhaps 10 kHz to 300 GHz) and it is well nigh impossible to extend research to the whole spectrum, to low and high levels of field, different modulation methods and so on. This is further complicated by the suggestion that some effects only occur in RF frequency 'windows' and modulation frequency or pulse rate 'windows'.

The term 'window' here implies that an effect has been claimed to occur at some RF frequencies and not at others or at low field levels and not at higher field levels of the same frequency or that the effect occurs at certain modulation rates and not at others. The variables, RF frequency, RF amplitude, modulation frequency and type, provide an almost infinite number of combinations to be studied. This illustrates the real difficulty in determining which combinations to explore. In more practical terms there is also the cost of equipment capable of generating all the frequencies and modulations at levels large enough for practical work.

It is scarcely surprising that from time to time some particular research may be challenged, either because of something related to the experimental situation or because of the conclusions drawn. In general the replication of research findings elsewhere is looked for but is not easy to achieve when finance is not available to pay for the work.

Some individuals express extreme views on RF radiation hazards, which are often drawn from the research of others, but which differ from those of the researchers concerned and from those of others working in the field of RF radiation. Where such views are genuinely held and the person concerned has a reasonable competence to handle the research concerned, this is no problem. It may even provide some impetus for more research, if the views are not so extreme as to be ignored.

The real problems occur when extreme views are expressed in the media without adequate background material, causing alarm in susceptible people who, for the most part, do not have a specific knowledge of the subject and cannot distinguish a legitimate lone voice from the general body of opinion on the subject. It is an unfortunate fact of life that people are very easily frightened by the media and often do not accept reassurance from those more familiar with the subject.

An even more worrying fact is that many people understand radio radiation as being synonymous with nuclear radiation, an aspect mentioned in respect of the public in Chapter 1. Since the latter is well known as a dangerous type of radiation, it can easily be seen why people continue to attribute the most serious effects of ionising radiation to radio frequency sources. The use of anonymous questionnaires at safety lectures has shown that such fears apply also to some technical people, including science graduates.

As a result, much time has to be given by RF safety specialists to explaining to technical people the difference between these two types of electromagnetic radiation and to explaining current views on RF radiation. It has to be said that reassuring people is not easy nor can it be totally authoritative since surprisingly little is known with any real certainty on the subject of RF radiation. Usually, the most that can be said is that there is no evidence to support a particular viewpoint.

It is interesting to note that other forms of electromagnetic radiation such as visible light and infrared radiation do not excite a great deal of public interest although photons of these have a much greater energy than RF radiation. The longest visible light wavelength has a photon energy of about 1.7 eV whereas the photon energy of the top end of the RF spectrum (300 GHz) is more than one thousand times less. Even ultraviolet radiation, for which the shortest wavelength portion of the spectrum at 100 nm and below is ionising radiation capable of quite serious effects, only invokes a modest amount of public concern.

The task of determining safe limits for RF radiation guides and standards is particularly difficult due to the lack of any substantive knowledge of the effects of RF radiation other than those concerned with direct thermal effects, shocks, burns and induced body currents at the lower frequencies. Most safety limits are determined by balancing benefits against risks and consequences and the latter are not well enough understood to permit this approach.

Notwithstanding such difficulties, standards for RF radiation safety are needed and practical safety limits for everyday work have to be set by some sort of consensus amongst those experienced in the field, having regard to such research as is available. If the limits are just set arbitrarily low, the use of RF power may become a serious practical problem, without offering any assurance that the low limits actually achieve anything.

It is not the purpose of this chapter to seek to resolve the differing views of the various factions interested in the debate on electromagnetic fields but rather to provide a broad outline of those known hazards of RF fields which are accepted by bodies concerned with producing safety standards, and to mention some of the areas of current investigation. A useful report which provides more details of the medical aspects, reviewing the findings of many research papers is the UK NRPB report NRPB-R240 [3].

Generally speaking the chapter is concerned with RF radiation down to about 10 kHz and does not therefore address the question of power frequencies (50 and 60 Hz). There is a great interest in the safety aspects of the fields from power frequencies and reference should be made to published papers on the subject including WHO publication number 25 [12] which deals with this and a number of other subjects, in addition to radio frequencies.

We can define the potential hazards of RF radiation in terms of:

1 Direct effects on people:
   (a) thermal effects attributable to the heating of the human body due to the absorption of RF energy. At lower frequencies this includes heating due to excessive current densities in some parts of the body.
   (b) shocks and burns which may result from contact with ungrounded conductors located in electromagnetic fields.
   (c) the so called 'athermal' effects where it is postulated that the fields act directly on biological tissue without any significant heating being involved.

2 Indirect effects on people wearing implantable devices such as heart pacemakers, insulin pumps, passive metal plates and other related hardware.

3 Effects on flammable vapours and electro-explosive devices, e.g. detonators (dealt with in Chapter 5).

Category 3 above may, of course, also involve people who may be present near the subject and may be affected by fire or explosion.

Some aspects of these topics may be differentiated in a general way in relation to the frequencies involved. The basic philosophy postulated in the IEEE C95.1–1991 standard [4], is that quasi-static considerations should apply at the lower end of the frequency spectrum and quasi-optical considerations at the upper end (above 6 GHz). The key factors are:

1 Below 100 kHz current densities induced in the human body and the electro-stimulation of tissues are considered to be the limiting factors.
2 From 0.1 MHz to 6 GHz, specific absorption rate (SAR) is the relevant factor.
3 Above 6 GHz, power density limits are used to control exposure.

In order to limit burns and shock at frequencies below 100 MHz, the permitted electric field strength is specifically limited. Below 300 MHz in this standard, both the electric and magnetic fields must be separately measured. Between 30 and 300 MHz there is a possible easement of the requirement if it can be shown by analysis that measurement of one of the fields is sufficient to secure compliance with the standard.

Note that other standards differ with regard to the frequencies at which electric and magnetic fields have to be measured separately. This is usually indicated by the absence of power density limits for those frequencies in the standard concerned, or their presence for information only.

Occupational and public safety limits

There is one general issue amongst those creating standards which results in strong differences in views. This is the question of whether separate limits are needed for these two groups. The wider issue of standards is dealt with in Chapter 4 but it is useful here to look at the arguments on both sides because they touch on harmful effects.

Some people feel that since there is no accepted concept of 'dose' for RF radiation such as exists for ionising radiation, there is no scientific case for separate limits for the two groups. (As a basic concept, dose = dose rate multiplied by the exposure time.) Consequently such people see the issue as a social and political matter. On the other hand some people believe that the duration of exposure is a significant factor in determining risks. It is true that, in general, populations feel protected if they are subject to tighter limits than those whose occupation requires them to be exposed. This is probably a universal feeling to which most of us would subscribe, especially if it relates to some occupation other than our own.

There could be a case on these grounds alone for lower limits for the public, though there are economic costs for such a decision. A factor often overlooked is the general acceptance by most bodies that the 'public' includes those non-technical personnel working for organisations using RF radiation. Thus there is a mixing of groups in employment and some sort of segregation is implicit.

The medical aspects raised include:

Members of the public include the chronic sick, including people with impaired functions such as the thermo-regulatory functions and who may therefore be subject to risks which might not apply to fit people.

The suspicion that RF radiation may have undesirable effects on people taking some types of drugs for medical conditions.

The fact that the athermal effects of RF radiation may eventually prove to have adverse effects on human health.

The possibility that RF radiation effects are cumulative, i.e., related in some way to 'dose'.

As it can be seen, these statements are of the precautionary type, the argument being that those who have to work with RF radiation choose to do so but the public in general have not made any such choice.

The fact that the arguments either way are not proven does not preclude the taking of a decision which is believed to err on the safe side, though the economic consequence is the cost involved in segregating the two groups, especially where the limitations of land ownership or occupation affect radiation levels at the interfaces with the public.

The IEEE C95.1–1991 standard, referred to earlier, tackles this problem by defining the need for RF radiation safety measures in terms of 'areas' rather than groups of people, namely 'controlled areas' and 'uncontrolled areas'. The former is an area where people who are knowledgeable about RF radiation are employed. The latter covers all the other employees. Extra safety factors are included for the last category. This concept of control by segregated areas broadly follows the practice for ionising radiation, though it would be very undesirable for the comparison to cause any confusion between the two types of radiation.

As can be seen from the discussion in Chapter 4, some standards only have one set of limits for all people, whilst others have separate provisions for occupational work and for the 'public'.

Specific absorption rate (SAR)

This term was used earlier and needs some explanation in the context of safety assessments. It is used to quantify the absorption of energy in tissue and is expressed in watts per unit mass of tissue, usually Wkg^{-1}. It is convenient to use the concept of the 'standard man' to aid discussion of the thermal aspects of RF radiation. The generally adopted standard man has a height of 1.75 m (5 ft 9 in), a weight of 70 kg (154 lb) and a surface area total of 1.85 m^2 (20 sq ft).

It is easy to see that the weight of the standard man is part of the definition of SAR so, for example, if it is known that the total power deposited in the standard man is 7 W, then the average whole-body SAR is 7/70 Wkg^{-1} or 0.1 Wkg^{-1}.

A 'worst-case' expression to relate specific energy absorption and temperature providing that the effect of cooling is neglected is given by the NRPB report [3] as:

$$T = J/(c \times 4180)$$

Where:
T = temperature rise (°C)
J = specific energy absorption (Jkg^{-1})
c = relative heat capacity (= 0.85)
Note also that J (Jkg^{-1}) = SAR (Wkg^{-1}) × exposure (seconds)

Hence a SAR of 2 Wkg^{-1} for 30 minutes will give a temperature rise of 1°C, neglecting cooling.

At very low frequencies (tens of kilohertz) energy absorption is relatively low. Absorption increases to a maximum at human resonance, which for adults is somewhere between 30 and 80 MHz depending on height and whether the person is effectively earthy or not. Above resonance absorption declines somewhat.

There is no practical way of measuring the SAR of a human being. In order to make calculations of SAR, either computer modelling or practical experiments with dummy persons using substances which simulate the electric characteristics of human tissues are undertaken.

Practical studies which simulate the human body use either standard shapes of hollow plastic objects such as spheres or hollow plastic human models generally known as phantoms. Their construction will depend on the temperature measurement technique to be used.

The most common systems are infrared (IR) scanning and temperature recording systems or the use of implantable temperature probes connected to some form of controller and data logger.

Phantoms in which implantable probes are used may be filled with a liquid or semi-liquid media simulating human tissue. This may be a homogeneous filling or elaborate layering and scaling may be done to represent the bones and organs of the human body with their different tissue simulations. The latter is obviously more expensive in time and materials, but can provide some differentiation of tissues.

In the case of phantoms to be used with IR thermography, the phantom can be bisected in the planes of interest, vertical and horizontal and flanges fitted to facilitate dismantling and assembly at the sections.

Again the simulation of tissue may be homogeneous or structured. The open faces of the sections are often covered with a close woven material which will ensure electrical contact of the two halves when assembled.

The complete phantom is exposed to a known uniform RF field for a specified time. The phantom is then split at the relevant sections and their open faces subjected to IR thermography to provide a plot of temperatures. In fact there will usually be two scans, one before the phantom is exposed and one after so that the temperature changes can be recorded.

Whichever type of system and phantom is used, the object is to calculate either whole body SAR or, sometimes, a local SAR. With probe systems, it is important that the probes should not perturb (distort) the RF field. A paper by Stuchly *et al.* [5] illustrates the scanning probe arrangement, using a non-perturbing probe system. Phantoms do not simulate the thermo-regulatory system of the human body and the results cannot be regarded as indicative of the temperatures likely in a live healthy human body.

Computer modelling attempts to model the human body by sub-dividing it into cells and attributing the relevant characteristics to each cell by analogy with the structure of a human being. There are limitations resulting from the deficiencies of any given model relative to a human body both in respect of the static model and the modelling of the dynamic performance of the complex thermo-regulatory mechanism of the human body.

The validation of computer modelling is difficult since it is generally only possible to compare it with some experimental trial such as the phantom method described above, despite the limitations of the method. Another paper by Speigel *et al.* [6] illustrates both a computer simulation and the comparison of the results with a phantom model.

Although one can identify the problems these methods pose, it has to be recognised that it has not yet proved possible to devise any other measurement method.

Thermal effects

General

There is general agreement that the main demonstrable effect on the human body is the thermal effect, i.e., the transfer of electromagnetic field energy to the body. A very high percentage of the human body is made up of water and water molecules are polar molecules liable to be influenced by impinging electromagnetic fields. Hence those tissues having a significant water content are most liable to be influenced by fields. Some other tissues also have large polar molecules

The effect of RF on such body tissues is to cause polar molecules to attempt to follow the reversals of the cycles of RF energy. Due to the frequency and the inability of the polar molecules to follow these alternations, the vibrations lag on them, resulting in a gain of energy from the field in the form of heat which causes an increase in the temperature of the tissue concerned.

With the widespread use of microwave ovens, most people have a practical awareness of the fact that microwaves can heat tissue, as represented by the animal tissues used in cooking, and should not find it too difficult to understand the nature of the thermal hazard. The amount of heating depends on the amount of energy absorbed and the activity of the human thermo-regulatory system. In turn, the amount of energy available depends on the power of the source and the duration of the exposure, 'cooking time' in the oven context.

Human thermo-regulation

In the healthy human body, the thermo-regulatory system will cope with the absorbed heat until it reaches the point at which it cannot maintain the body temperature satisfactorily. Beyond this point, the body may become stressed.

Excessive exposure can give rise to hyperthermia, sometimes referred to as heat exhaustion, an acute, treatable condition which, if neglected could have serious results. Excessive heating can also cause irreversible damage to human tissue if the cell temperature reaches about 43°C.

The author has never come across a case of hyperthermia in connection with RF radiation even with the highest power transmitters. This is possibly attributable to the commonsense of those who work with them. Nevertheless, with some equipment installations there is the potential for excessive exposure which, in the worst scenario, might have very serious consequences, so there is no room for complacency.

A rise in body core temperature of about 2.2°C is often taken as the limit of endurance for clinical trials [7]. For RF radiation purposes, a limit of a 1°C in rectal temperature has often been postulated as a basis for determining a specific absorption rate (SAR) limit for human exposure. Most western occupational standards are based on an SAR of $4\,\mathrm{W kg^{-1}}$ divided by ten to give a further safety margin. Thus the general basis is $0.4\,\mathrm{W kg^{-1}}$.

It should be noted that people with an impaired thermo-regulatory system or with other medical conditions which affect heat regulation may not be so tolerant to the heating permitted by standards which have been set for healthy people. Those taking some forms of medication may also be affected adversely.

There are also factors other than general health which affect the ability of the human body to handle heat energy. For example, a period of strenuous physical work can elevate the rectal temperature.

Another factor is the environmental condition – ambient temperature and relative humidity can make a considerable difference in the ability of the human body to get rid of excess heat.

Consequently, a given SAR may, for a constant ambient temperature and specified exposure time, give different body temperatures if the relative humidity is changed from a high figure, say 80%, to a low one, say 20%. Put the other way round, a specific increase of rectal temperature of, say, 1°C will require a much higher SAR at low relative humidity than is needed at high humidity.

In 1969, Mumford[8] identified this aspect and proposed a 'comfort index' whereby the higher safety level then in use (100 Wm^{-2} for all the frequencies covered) was reduced as his temperature-humidity index increased. Current standards such as the IEEE C95.1–1991 standard claim to accommodate environmental factors in the large contingency allowance put into the permitted limits.

A particularly interesting paper on the thermo-regulatory mechanisms of the human body is that of Adair[9]. The paper describes the regulatory mechanism in some detail. It notes experimental work done to establish the thermal equivalence of heat generated in the body during physical exercise and passive body heating such as that from HF physiotherapy equipment.

It also makes reference to the radical difference between the thermal responses of man and various animals and the consequent difficulty in extrapolating animal exposure data to human beings on this account, quite apart from any resonance differences.

RF penetration in human tissues

In considering the amount of energy absorbed by the human body, it is necessary to recognise that the percentage of incident radiation which is actually absorbed depends on frequency and the orientation of the subject relative to the field.

In human tissues, RF radiation may be absorbed, reflected or may pass through the tissue. What actually happens will depend on the body structure and the tissue interfaces involved. These interfaces are the transitions from tissue to tissue or tissue-air-tissue and are clearly complex in the human body.

The depth of RF penetration of the human body is also an important factor. In the HF band, the deeper penetration is used for diathermy treatment where the deposition of heat is intended to have a beneficial effect on that part of the body considered to need treatment. The deep deposition of RF energy needs to be carefully controlled to avoid damage to tissues which might not be noticed by the subject due to lack of sensory perception of heat in the organs concerned.

The measurement of the RF characteristics of human tissue can, for the most part, only be done with chemical simulation of tissue, since there are problems with the use of excised human tissue for this purpose. The penetration depth is usually given as the depth where the incident power density has been reduced by a factor of e^{-2}, i.e., down to about 13.5% of the incident power density.

The penetration decreases as frequency increases. Figure 3.1 has been drawn using some of the data from published tables, the work of Schwan,

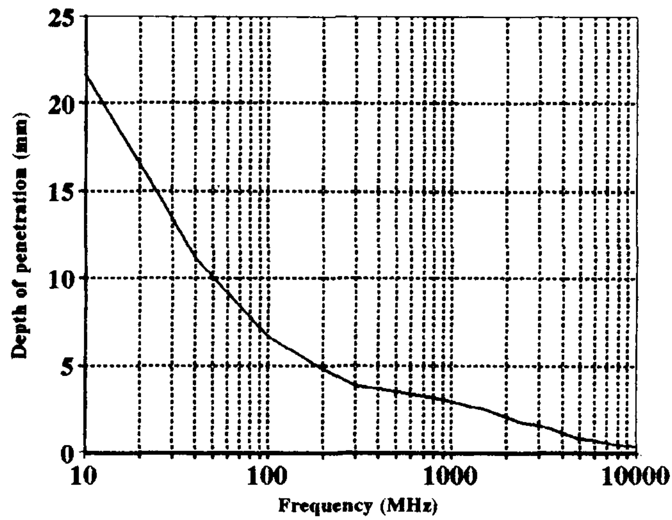

Figure 3.1 *Depth of penetration of RF energy in tissues with high water content (data from reference 10).*

Cook and Cole and other researchers. The tables are given in a paper by Johnson and Guy[10]. It illustrates laboratory calculated penetration depths versus frequency for tissues with high water content.

The illustration should only be considered as giving a rough picture of the change of penetration depth with frequency as the laboratory determination of these data is subject to various factors including temperature dependency. Tissues with a low water content have significantly deeper penetration.

At the microwave end of the RF spectrum, deposition of energy is confined to the surface layers of the skin. The penetration depth at the higher microwave frequencies may only be a few millimetres[11]. Deposition of energy in the surface layers of the skin may lead to thermal injury, the risk increasing as the frequency increases.

Resonance

It has been seen how the weight of the standard man is linked to the use of the concept of specific absorption rate. The purpose of a standard height may be less obvious. To see the effect of this it is necessary to consider how the absorption of energy is affected by frequency.

It is also necessary to define the attitude of the model relative to the plane wave field to which it is subjected.

Figure 3.2 shows the average SAR in a spheroidal model man subjected to a field of 10 Wm^{-2} and displayed in three curves [12]. The curves are labelled

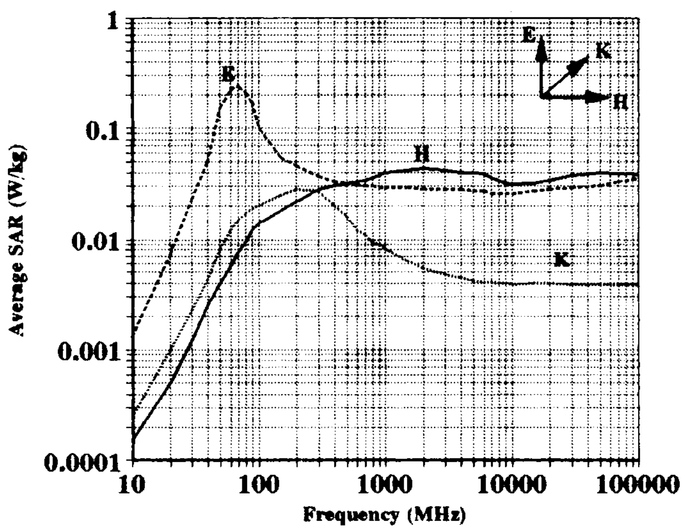

Figure 3.2 *SAR versus frequency for orientations parallel to the E, H, and K vectors*
(Courtesy the World Health Organisation, European Office)

E, H and K and indicate that the model man was successively orientated parallel to the electric field (E), the magnetic field (H) and the direction of propagation, head to toe (K).

Considering the curve E, it can be seen that absorption is lowest and declining rapidly with decreasing frequency at 10 MHz. It increases rapidly with increasing frequency to peak at about 70 MHz. The peak represents 'resonance' of the model man.

Put simply, this means that at the resonant frequency, the absorption of RF energy is at a maximum. The reader unfamiliar with electrical resonance may be familiar with mechanical resonance where at a given frequency some object which is excited with constant power over a range of audio frequencies, manifests a large amplitude of vibration at one particular frequency. The energy involved may then result in acoustic noise and possibly the eventual fatigue of materials.

Returning to the RF resonance case, the resonant frequency is related to the height of the erect person. Resonance occurs when that height corresponds to approximately 0.36 to 0.4 wavelengths.

Hence using 0.4 for the standard man, $\lambda = 1.75/0.4 = 4.37$ m and the frequency is approximately 300/4.37 MHz = 66 MHz.

If the subject is effectively earthy due to bare feet or conductive shoe material, the resonance will occur at half the above frequency, i.e., about 33 MHz. Table 3.1 gives a few examples for subjects who are non-earthy,

Table 3.1 *Effective resonant frequency for an erect person in a vertically polarised field versus height using the relationship $h = 0.4\lambda$*

Subject height (metres)	*Resonance (MHz)*
0.5	240
0.75	160
1	120
1.25	96
1.5	80
1.75	68.6

using the 0.4λ calculation. Small children obviously resonate at higher frequencies and tall adults at lower frequencies.

Hence a frequency band can be established which covers all people, large and small. Strictly, the occupational frequency bandwidth for resonance is smaller since the range of heights for employed people is smaller.

Gandhi[13] states that at resonance a human being absorbs energy 4.2 times greater than that which might be expected from consideration of the physical cross-section of the body. Further, when the person is effectively earthed, the resonant frequency is reduced to approximately half of that for the non-earthy condition and the energy which is absorbed is about 8 times that expected from consideration of the physical cross-section. Another way of conceiving this is that the effective electrical cross-sectional area of the exposed person is several times that of the actual cross-sectional area at resonance.

It will be noticed in Figure 3.2 that the electric field curve (E) indicates that the electric field gives rise to more absorption than the magnetic field curve (H) up to about 700 MHz, the difference being considerable over much of that frequency range.

Hot spots

The human body is made up of a mixture of types of tissue, for example, skin, blood, bone, muscle and fat. When the human body is exposed to RF radiation, there is, as described earlier, some degree of absorption of the energy in the form of heat. However, the absorption of RF energy in the human body which is made up of such a complex mixture of tissues, can result in a non-uniform distribution of heat. Hot spots (high local SARs) may occur in the human body over the range of about 30 to 400 MHz. These hot spots will be evident at frequencies around body resonance where absorption is greatest and at sub-resonances in parts of the body. Gandhi[14] gives the adult human head resonance range as being of the order of 350 to 400 MHz with a volume–averaged SAR of 3.3 times the whole-body SAR at resonance and the absorption cross-section as about three times the physical cross-section.

He also gives some local SAR values for knees, ankles and the neck for body resonance in the grounded man (about 34 MHz) and the ungrounded man (about 68 MHz).

The measurements were made with scaled human phantoms and showed hot spots at the knees, ankles, elbows and, in the case of the non-earthy model, the neck. These have some 5 to 10 times the average whole-body SAR.

It is difficult to tackle the problem of non-uniform heat absorption by seeking to identify the location and temperature of such hot spots. Using physical models poses the problem of carrying out measurements without affecting the distribution and magnitude of the effects due to the presence of the measuring devices and, as mentioned previously, physical models cannot simulate the human thermo-regulatory system.

Work has been done on the subject of 'hot spots' using computer modelling but this again poses the problem of validating such models as being an adequate and correct representation of the functioning human body. The reason that attention has been given to this problem is a simple one. If a safety standard defines a safe power density limit for a particular frequency on the basis of the average whole-body SAR but some small parts of that body reach significantly higher temperatures than others, there must be concern as to whether these can be harmed in some way.

Some high ratios between mean body temperatures and hot spot temperatures have been noted[3]. Ratios suggested from experiments using magnetic imaging range from 10 to 70, though this reduces to a factor of 2 to 4 when the SAR is averaged over individual organs.

The theoretical end point could be where the hot spot is so hot as to cause cell damage, in which case it would be necessary to adjust the average permitted levels to reduce the hot spot temperatures. It has to be said that little is known about the real effects in a healthy individual with an efficient thermo-regulatory system as contrasted with computer or model simulation.

A paper by Gandhi and Riazi[11] looks at the power capabilities of RF sources in the frequency band 30 GHz to 300 GHz and identifies the possibility of high energy deposition rates for the skin at frequencies in that range due to the very shallow penetration depths. It also looks at the possibility that dry clothing may act as an impedance transformer, increasing the amount of energy coupled into the body. The thickness of clothing in this frequency band is a significant fraction of the incident wavelength. This could, for a given incident power density, exacerbate the situation by further increasing the deposition in the superficial layers of the skin.

The IEEE C95.1-1991 standard recognises the problem of energy deposition in the superficial skin areas by progressively reducing the averaging time for exposures at above 15 GHz from the usual 6 minutes to a shorter period.

Susceptible organs

From the thermal transfer point of view, the two organs which are considered more susceptible to heat effects than others are the eyes and the male testes. Neither of these have a direct blood supply and hence do not have that means of dissipating the heat load.

Effects on the eyes

The production of cataracts in animal experiments using RF has been well established. It is generally considered that this effect is a thermal one. Experimental work has been limited to animals and the different physical characteristics of the eye structure in different types of animal do give rise to different results. Also, the depth of penetration of the eye tissues is dependent on the frequency of the radiation.

It is thought that for human beings the frequencies most likely to cause cataracts lie between 1 and 10 GHz and probably require power densities of 1000 Wm^{-2} to 1500 Wm^{-2}. Whilst it is easy to do animal experiments with small localised fields, in practice, people exposed to RF fields related to antenna systems are likely to experience whole-body radiation and these sort of levels for whole-body radiation are far in excess of those permitted for microwave work.

Some recently reported work claims that microwave radiation at low levels, particularly with pulsed radiation, can affect susceptible parts of the eye. Gandhi and Riazi[11] referred to experiments on rabbits at 35 GHz and 107 GHz where some eye damage (albeit reversible) had been sustained with a total absorption in the eye of 15 to 50 mW.

They suggested that at millimetric wavelengths, the power absorption of the human eye might be of the order of 15 to 25 mW for an incident power density of 100 Wm^{-2} after 30 to 60 minute exposures.

It was considered that studies of exposures longer that 60 minutes are needed to investigate this. If the estimates are found to be true, there will be some reason for concern about the new power density limits for these frequencies in the latest standards.

From other sources, some low thresholds for harmful effects have been reported for cases where a substance used for eye treatment (timolol maleate), had been applied. If this work is subsequently confirmed by others, the whole subject may need further investigation.

In the author's view there is often unnecessary exposure to the eyes, for example by holding the head close to open RF amplifier circuitry when aligning or diagnosing on a bench without bothering to switch off. These can usually be avoided by better safety disciplines and by the use of modern optical aids including optical fibre inspection equipment.

There is similarly a need for caution in working with RF radiation so as to avoid the unnecessary eye exposure which can sometimes occur where waveguide flanges are removed without the source being switched off, and worse still, by the silly practice of looking down such waveguides. Although people think that the old practice of looking down the waveguide with power on to look at the electronic tube stopped long ago, cases have arisen as recently as three years ago!

Effects on the testes

Experiments with anaesthetised mice and rats showed[3] that male germ cells are depleted by exposure to SARs of about 30 $\mathrm{W kg^{-1}}$ and 8–10 $\mathrm{W kg^{-1}}$, respectively. Conscious mice exposed to 20 $\mathrm{W kg^{-1}}$ and 9 $\mathrm{W kg^{-1}}$ respectively, did not show any effect. The difference is regarded as being due to the fact that the anaesthetised animals were not able to regulate their testicular temperature. Other studies with rats reported a transient decrease in fertility with an SAR of about 6 $\mathrm{W kg^{-1}}$.

There seems to be little if any published information regarding such problems with human adult males. It seems likely that the whole-body SAR required to produce a sufficient temperature increase in the testes of an adult male would produce some basic signs of warmth and discomfort, resulting in withdrawal of the subject from the RF field. This is, of course, purely speculative since the author is not aware of any research carried out with men. However, with many years working in a large organisation manufacturing high power transmitters, no complaint of this kind has arisen.

Hearing effects

It has long been known that some people can 'hear' the pulse repetition frequency of radars and similar equipment. In this field it is not usually difficult to find human volunteers for tests so that there is no problem of relating other animals to people.

It is therefore surprising that more work has not been done in this field. The work of Frey[15] reported in 1961 involved tests with volunteers using two transmitters of frequencies 1.3 GHz and 2.9 GHz, the former being pulsed with a 6 μs pulse (244 Hz repetition rate) and the latter with a 1 μs pulse (400 Hz repetition rate).

He gave the mean power density threshold of hearing for those able to hear anything as 4 Wm^{-2} and 20 Wm^{-2} respectively.The corresponding peak pulse power densities were 2.6 kWm^{-2} and 50 kWm^{-2}. It was stated that the human auditory system responds to frequencies at least as low as 200 MHz and at least as high as 3 GHz.

In another paper, [16] Frey reported that the sounds heard included buzzing, hissing, and clicking and depended, among other things, on the modulation characteristics. In these tests Frey used a frequency of 1.245 GHz. A constant repetition rate of 50 Hz was used and longer pulse widths (from 10 to 70 μs).

The pulse width was changed to adjust mean power and peak power densities. The volunteers were required subjectively to assess the loudness of the sound heard relative to a reference sound which had been transmitted.

The general finding was that the perceived loudness was a function of the pulse peak power density, rather than the average power. The peak power density for perception was less than 800-Wm^{-2}.

The nature of the effect has been the subject of much investigation[17]. It seems generally agreed that the pulsed RF energy causes an expansion in the brain tissue due to the small but rapid temperature change involved.

This causes a pressure wave which is transmitted through the skull to the cochlea where the receptors respond as for acoustic sound. It is not necessary to have the middle ear intact. The temperature increase which causes the pressure wave is considered to be less than 10^{-5}°C.

It is perhaps worth noting that sometimes the pulse repetition frequency of high power radars can be heard from objects such as old wire fencing, and this can easily be confused with the above phenomena. Presumably the effects on old fences involves some form of rectification of the RF currents due to corroded junctions within the fence, and the consequent vibration of some fence elements at the pulse repetition rate.

Although the results of laboratory tests have been published, little, if anything, seems to have been published in recent times regarding the practical experience of those working on transmitting sites and any problems they may have noticed. With the low levels mentioned as thresholds for hearing, it might be thought that many radar personnel would experience this phenomenon.

A survey was carried out by the author across 63 engineers working with the transmitting side of radar. Many of the participants had 30 years or more experience in that work. The survey has no scientific basis, being limited to the collection of anecdotal evidence from those concerned by means of a questionnaire.

The results were interesting in that only three people claimed to have heard the pulse repetition frequency (or sounds related to it) and for two of these, each cited only a single experience in unusual circumstances. Both occurred on a customer's premises, during the Second World War.

Both of these people considered that the circumstances led to exposure to very high fields but there was no measuring equipment available in those days and in consequence, little safety monitoring. The third case was interesting in that it seemed to imply a different mechanism, one which has occasionally been reported in the past. This person claimed that he had heard the pulse repetition frequency on a customer's premises and attributed this to a tooth filling. (The Frey work in 1961 did include the use of shielding to exclude the 'tooth filling' possibility.)

It was further claimed that this ceased when the tooth was extracted. Strangely enough, another person who gave a negative answer to the basic question did claim to hear a local radio amateur when at home, again attributing this to a tooth filling with the same claim that it ceased after the tooth was extracted!

Outside of this survey, there was one engineer in the same organisation who regularly claimed to hear the pulse repetition frequency on company premises, but was able to live with it. This applied in an environment which was maintained within ANSI C95.1-1982.

This account is again anecdotal, the experience extending over a number of years. It was the only case in which this phenomena occurred on company premises.

Assuming that none of the respondents to the questionnaire had chosen to suffer in silence, this particular company, which designs and manufactures high power civil and military radars, does not seem to have a problem with auditory effects despite the high radar peak powers usually involved and the fact that much of their high power work lies within the 0.8 to 4 GHz frequency range.

Limb currents

Up to about 100 MHz, theoretical consideration of currents induced in the human body and especially the limbs, has given rise to some concern. As a result, research has been carried out to ascertain the magnitude of RF currents induced in the human body. It has been established that currents in the legs of an adult in an RF field may give rise to large SAR values at places where the effective conductive cross-sectional areas are small. Hence, the current density will be much larger than that implied by consideration of the actual cross-sectional area at that place. The knee and the ankle are examples of such areas, and some attention has therefore been given to SAR values associated with them, particularly the ankle.

Gandhi and Chen[18] have shown by measurements made with people that the induced currents are highest when the human body is erect and barefoot, i.e., earthy, and parallel to a vertically polarised plane wave field. The leg currents are proportional to frequency and to the square of the height of the person exposed.

An approximate formula (up to about 27 MHz) for the current in the leg of an erect barefoot person where the electric field is vertical is given as:

$$I\ (\text{mA})/E\ (\text{Vm}^{-1}) = 0.108 \times h^2 \times f\ (\text{MHz})$$

where h = subject height (m), f = frequency (MHz) and E = electric field (Vm^{-1})

Example:

For a field $E = 60\ \text{Vm}^{-1}$; $f = 1\,\text{MHz}$; $h = 1.75\,\text{m}$:

$$I\ (\text{mA}) = (0.108 \times (1.75)^2 \times 1) \times 60 = 19.85\,\text{mA}.$$

Above 27 MHz, the measured currents peaked around 40 MHz, reflecting resonance of the subject. An empirical expression for current above 27 MHz which includes an element representing the resonance frequency of the 'standard man', gives a sine wave shape for I/E versus frequency.

At field limits corresponding to the ANSI C95.1-1982 standard electric field limits[19] for frequencies from 3 to 40 MHz, values of SAR at the ankles of 182 to 243 Wkg^{-1} have been reported from tests carried out. Ankle currents were reduced when footware was used, depending both on the frequency and on the electrical properties of the material of which the footware was made. The current when wearing shoes ranged from 0.8 to 0.82 times the barefoot current. Previous work at 1 MHz showed corresponding fractions as 0.62 to 0.64. The increase with frequency is due to the fall in the impedance to ground as the frequency increases.

Another paper by Chen and Gandhi[20] illustrates the task of computer modelling the human body in order to establish the RF currents induced over the frequency range 20 to 100 MHz. The results of the calculations are presented in a series of graphs. The results are said to agree with experimental data produced by other workers.

RF safety standards now include limits for the values of leg currents up to 100 MHz as well as contact current limits to prevent shocks and burns.

RF shocks and burns

At low frequencies and up to about 100 MHz, contact with passive objects in RF fields may result in currents flowing through that part of the body in contact, usually the hands, causing shock and sometimes burns.

These effects can result from contact with almost any conductive object such as fences, scrap metal, unused dish and similar antennas or other equipments stored in the open, vehicles, farm machinery, metal buildings, etc.

Burns may result when the current density ($mAcm^{-2}$) is excessive due to the contact area being relatively small. The possibility of a burn is reduced with the greater area of a full hand grasp. However, this is rather academic since contact is usually inadvertent and often involves the finger tips.

A paper by Chatterjee *et al.* [22] deals with the measurement of the body impedances of several hundred adult subjects, male and female, over the frequency range 10 kHz and 3 MHz. Experiments were also carried out on threshold currents for perception and for pain. It was generally found that up to 100 kHz the sensation experienced was that of tingling or pricking and above 100 kHz the sensation was one of warmth. The calculated current for contact with the door handle of a van of effective area of 58 m^2 and 0.5 m effective height at 3 MHz is given as 879 mA when the field is 632 Vm^{-1}.

Because of the fact that burns essentially result from the current density at the point of contact and hence the effective contact area, it is quite possible to experience currents exceeding a given standard without incurring burns, purely as a result of a fortuitously large contact area. It is clearly important to measure contact currents rather than operate on the practice of assuming that if no burn occurs then there is no hazard.

It should not be overlooked that parts of the body other than the hands may incur burns. A common example is where shorts are being worn, as the bare leg may contact metal objects. People have also been known to sit on metal objects when wearing shorts.

Present views on a limit for occupational exposure to contact current over the frequency range 0.1 to 100 MHz seem to range from 100 mA to 20 mA. Touch burns have been predicted as possible at 60 mA with a contact area of 0.2 cm^2.

Apart from the undesirability of incurring shocks or burns, there are other indirect effects which, in the writer's experience, can be more worrying. Quite small shocks incurred by people working on structures can result in an involuntary movement (startle response) and a possible fall. Current safety standards are not likely to prevent these small shocks.

In a number of cases where a contract to fit new antenna systems on working sites has been involved, construction staff have started assembly and noticed 'sparks' between tools and the structure. Consequently, there has been considerable alarm because of the general fear of radiation and because of the awareness of the possibility of 'startle response' accidents.

In a number of these situations, the result has been a temporary cessation of work. The subject therefore needs more attention than the mere observance of the provisions of a safety standard regarding contact current since the probability is that these apparently minor manifestations may occur at lower limits and have indirect physical and psychological effects.

There will often be two cases to consider as far as contact with conductive material in an RF field is concerned. The first case involves the safety of people employed on a site or on company property and in most countries there are provisions for health and safety at work. The problem lends itself to good safety management which should include the prohibition of the dumping of metal objects in such fields. The second case is that of the public who own or have a right of access to adjacent land which may be irradiated by RF. Here those who own or lease such land have a right to use and deposit conductive objects where they wish and there is a duty on those responsible for the RF emitter to ensure that those people cannot receive shocks or burns from objects on their own property.

It may even be necessary to reduce the radiated power or change the antenna characteristics in order to ensure that this is so. The same applies to land on which the public may have a right of access, possibly with bicycles and cars. Vehicles in particular can give rise to significant contact current when in an RF field and since there are often a lot of them about, this can be a significant problem even if it only causes annoyance rather than real injuries.

Perception of a sensation of heat in RF fields

As mentioned earlier in this chapter, RF energy in the higher frequencies of the RF spectrum above perhaps 3 GHz can be detected by temperature sensors in the skin since, as the frequency increases, the energy is increasingly deposited in the outer layers of the skin. The indications resulting are dependent on a number of factors including differing heat sensitivity in different parts of the body, the duration of the exposure and the area exposed. WHO[12] notes that in tests on mammals the threshold temperature for cellular injury over seconds to tens of seconds (42°C) was found to be below the pain threshold (45°C). For this reason, the avoidance of the skin heating sensation does not provide a reliable protection against harmful exposures.

It is postulated that it may be a better indicator at frequencies of tens of GHz and higher where the wavelength is comparable with or less than the thickness of the skin. Prudence seems to suggest that it should be completely disregarded as an indicator until much more is known about all the variables involved.

There is a universally accepted statement about RF radiation work that people should not remain in a field which gives rise to a sensation of warmth even if the power density is within the permitted limits of a standard. It will be evident from the previous discussion that this does not guarantee that no harm has been incurred but is intended as an extra warning.

At frequencies well below those being discussed, the penetration of RF in the human body (page 49) is such that much more of it will be below the skin sensors and there may not be any physical sensation of warmth. The prevention of internal damage has to be by the limitation of exposure.

Pulsed radiation

Pulsed RF radiation is very common, typically in radar and in some data transmission systems. Pulse transmission is discussed elsewhere but the two aspects relevant here are the mean power density and the peak pulse power density. A typical radar may have a factor of 1000 between these so that, say, a mean power density of 50 Wm^{-2} would imply a peak pulse power density of 50 kWm^{-2}.

In the early days of RF radiation safety regulation, emphasis was on mean power and this left open the question of limiting the peak power density. As a result of concern expressed by some people, research has been undertaken to examine possible effects attributable to high peak power pulses.

Experiments with animals have indicated that the startle response to a loud noise was suppressed by a short pulse of microwave radiation. Body movements have also been induced in mice. Calculations suggest a large SAR value in these animals.

It is considered that pulsed radiation may have specific effects on the nervous system. Most standards now place a limit on peak pulse power density and pulse energy and this is discussed in Chapter 4.

Athermal effects of RF radiation

This term is used to describe any effect which is thought to arise by mechanisms other than that involving the production of heat in the body. It has been somewhat controversial, some people disputing whether such effects existed. However, most people now probably accept the need at least to investigate observations which do not seem to be linked to the thermal deposition of energy in the human body.

With regard to tumours, there seems to be a degree of consensus amongst most bodies.

This is probably best expressed in the UK NRPB press release on the report of the Advisory Group on Non-Ionising Radiation[23] which stated: 'We conclude from a review of all the evidence, including both that relating to humans in ordinary circumstances of life and that relating to animals and cells in the laboratory, that there is no good evidence that electromagnetic radiations with frequencies less than about 100 kHz are carcinogenic; this includes those produced by electrical appliances, television sets and video display units. With higher frequencies there is room for more doubt, some laboratory evidence suggesting that they may act as tumour promoters, although in this case the effect may be secondary to local tissue heating.' It goes on to recommend further research on the subject. A similar statement is made[12] in the World Health Organisation (WHO) publication No. 25.

Needless to say, there are people who do not subscribe to this view and since there are so many uncertainties reflected about the role of electromagnetic fields, if any, in cancer promotion, it is not possible to refute such views. The situation is often coloured by the fact that whilst we are all subject to the possibility of incurring this disease, some of those engaged in electrical and radio work who suffer the disease are inclined to attribute cancer to their occupation.

The topics encountered under the heading of 'athermal' effects cover almost everything to do with the human body. Reports and papers are very technical, requiring considerable practical familiarity with the subject matter. They range from the possibility of RF causing cancers as mentioned above, through the operation of all the systems and constituents of the human body, cells, tissues, organs, the immune system, reproduction, etc., to the psychological aspects claimed by Russian researchers.

These are not discussed further here but competent discussion of some or all of these topics can be found in references 3, 12 and 23 and in the standards and other national documents of various countries.

Effects on people wearing implantable devices

There are a number of implantable devices, active and passive, which are fitted into the human body. Perhaps the most common one is the heart pacemaker on which many people depend. There are two basic types of heart pacemaker. The first could be described as a demand pacemaker which will make up for missed heart beats as needed. The second type is the fixed pacemaker which operates continually at a fixed rate with no other form of control.

It is possible that some sources of RF radiation could interfere with the operation of pacemakers, the significance of such interference depending on the type of pacemaker fitted. The potentially more serious consequences of interference relate to interference with the fixed rate pacemaker. However, the two descriptions above are basic. With current developments in electronic devices there is always the possibility of the use of more sophisticated devices and the possibility of new problems of vulnerability to interference.

Many of these pacemakers are subjected to interference (EMC) testing by the manufacturer but the relevant information does not normally get communicated to the wearer of the device. Consequently, those responsible for the operation of RF transmitters and similar sources who may become involved with visitors wearing a heart pacemaker have no means of carrying out their responsibilities for the safety of such people.

The only recommendation that can be made is that such sites should have a sign requiring visitors to notify the manager that they are wearing a pacemaker. They can then be excluded from RF fields. A similar problem can occur at exhibitions where equipment is being demonstrated and where many people may be present.

There are other devices such as insulin pumps which are implanted and the views of medical authorities may need to be sought on these and any new types of implanted devices.

In the EEC there is a new Directive on Active Implantable Devices[66] but the current draft does not fully tackle the problem of the electrical characterisation of devices in terms of interference testing. There are also many types of passive devices fitted in the human body. These may include metal plates, rods and fixings. There is always the chance of these being resonant at the frequency in use at a particular site.

The author was involved in a case in the Middle East where a guard with a silver plate in his leg complained that it got hot when he was near a particular microwave transmitter. Such cases may not carry the same risks as that of pacemakers but can cause serious worries for people. For those employed with RF radiation, it seems desirable to record any such implants fitted when personnel are first employed and thereafter, should the situation arise. It is then possible to exercise supervision over the exposures to RF of such people.

In summary, the situation on all types of implantable devices is a dynamic one in which there is constant innovation. It may be necessary to ensure that surgeons and physicians have some understanding of the implications for those involved in RF radiation, so that their patients can be given meaningful advice.

Beneficial effects

Discussion of the effects of RF radiation on people would not be balanced without a brief reference to the beneficial effects which have been and are being applied in the medical field. Some aspects of this are discussed in Chapter 2 where a typical HF radiotherapy machine is illustrated.

Some recent uses are, in summary, as follows:

Bony injuries

There is considerable evidence that the application of RF energy at the site of a fracture speeds up the healing of both soft tissues and bony injuries. This is now fairly well established as a technique, though the mechanism by which such healing takes place has not been established with any certainty.

Treatment of malignant tumours

If cancer cells can be heated rapidly enough to the cell thermal death point, they can be destroyed. Microwave energy lends itself to application for this purpose. Current use is generally in association with other treatment, chemotherapy (cytotoxic drugs) or radiotherapy (ionising radiation). Getting the RF energy to the tumour site can be a problem and care is needed to avoid unnecessary damage to healthy cells.

Other organs

Techniques have been described which enable the application of RF to the male prostate gland to shrink the gland. Surgery is not needed and patients can usually return home the same day.

RF radiation effects summary

The induction of RF energy in the human body in the form of heat is accepted though there is a practical problem of establishing the amount of heat energy and its distribution in the body, due to the difficulties involved in direct measurement.

The susceptibilities of particular organs are known from considerations of the nature of the human body but practical experimental work is confined to animals with the consequent difficulty of extrapolating findings to human beings.

There is a body of knowledge on the subject of induced body currents since it is practicable to use volunteers for such work and measuring techniques have become available. There is also some knowledge of aural effects from human experiments.

Relatively little is known with any certainty about other possible effects, including those described as athermal effects, and much more research may be necessary to improve our knowledge in the face of the many difficulties, both technical and financial.

There is a body of knowledge, based on experimental work, for those indirect effects on people such as the inadvertent ignition of flammable vapours and electro-explosive devices. The information in respect of flammable vapours could easily be made into an international standard.

With the finite financial limitations on research across the world and the permutations of frequency, amplitude, modulation methods, etc., which might need to be explored, it seems necessary that such research should be organised and directed systematically to those topics which experts in the field feel to be priorities. In this way it might be possible to avoid the apparent randomness and fragmentation of present research and include provision for the independent replication of any seemingly important research results.