The Biological Effects of Weak Electromagnetic Fields

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What the power and telecoms companies would prefer us not to know

Foreword

There have been many instances of harmful effects of electromagnetic fields from such seemingly innocuous devices as mobile phones, computers, power lines and domestic wiring. They include an increased risk of cancer, loss of fertility and unpleasant physiological symptoms. The power and mobile phone companies, hoping to avoid litigation, often assert that because the energy of the fields is too low to give significant heating, they cannot have any biological effect. However, the evidence that electromagnetic fields can have "non-thermal" biological effects is now overwhelming. In this article, I will explain how these effects arise. I have included key references that should enable the more inquisitive reader to delve deeper. If you do, you will often find contradictory assertions and that the reproducibility of several experiments is only mediocre. As we will see, this is almost certainly because of differences in the genetic and physiological condition of the biological material and its ability to defend itself against electromagnetic insults. Defence mechanisms have evolved by natural selection over countless millions of years of exposure to natural electromagnetic radiation, such as that from thunderstorms. They can often hide the underlying effects of man-made fields so we do not always see them in our experiments. We therefore have to concentrate on the experiments that give positive results if we are to discover the mechanisms. In this context, negative findings (frequently published in work financed by the telecoms and power companies) have no meaning.

Abstract

1. Well-replicated studies have shown that weak electromagnetic fields remove calcium ions bound to the membranes of living cells, making them more likely to tear, develop temporary pores and leak.

2. DNAase (an enzyme that destroys DNA) leaking through the membranes of lysosomes (small bodies in living cells packed with digestive enzymes) explains the fragmentation of DNA seen in cells exposed to mobile phone signals. When this occurs in the germ line (the cells that give rise to eggs and sperm), it reduces fertility and predicts genetic damage in future generations.

3. Leakage of calcium ions into the cytosol (the main part of the cell) acts as a metabolic stimulant, which accounts for reported accelerations of growth and healing, but it also promotes the growth of tumours.
4. Leakage of calcium ions into neurones (brain cells) generates spurious action potentials (nerve impulses) accounting for pain and other neurological symptoms in electro-sensitive individuals. It also degrades the signal to noise ratio of the brain making it less likely to respond adequately to weak stimuli. This may be partially responsible the increased accident rate of drivers using mobile phones.
5. A more detailed examination of the molecular mechanisms explains many of the seemingly weird characteristics of electromagnetic exposure, e.g. why weak fields are more effective than strong ones, why some frequencies such as 16Hz are especially potent and why pulsed fields do more damage.

Introduction

The strange non-thermal biological effects of electromagnetic fields have puzzled scientists for decades and, until now, there has been no clear explanation. In this article, I will outline a new theory, based on experimental evidence gathered over many years, that explains how virtually all of these effects arise.

Firstly, it is not only humans that are affected. Well-researched responses in other organisms include the more rapid growth of higher plants (Smith et al. 1993; Muraji et al. 1998; Stenz et al. 1998), yeast (Mehedintu and Berg 1997) and changes in the locomotion of diatoms (McLeod et al. 1987). The last two are significant because they are both single cells, implying that the effects occur at the cellular level. Furthermore, we can explain virtually all of the electromagnetic effects on humans in terms of changes occurring at the cellular level that may then affect the whole body.

A few basic facts

Field strength: An electromagnetic field consist of an electrical, part and a magnetic part. The electrical part is produced by a voltage gradient and is measured in volts/metre. The magnetic part is generated by any flow of current and is measured in tesla. For example, standing under a power line would expose you to an electrical voltage gradient due to the difference between the voltage of the line (set by the power company) and earth. You would also be exposed to a magnetic field proportional to the current actually flowing through the line, which depends on consumer demand. Both types of field give biological effects, but the magnetic field is more damaging since it penetrates living tissue more easily. Magnetic fields as low as around one microtesla (a millionth of a tesla) can produce biological effects. For comparison, using a mobile (cell) phone or a PDA exposes you to magnetic pulses that peak at several tens of microtesla (Jokela et al. 2004; Sage et al. 2007), which is well over the minimum needed to give harmful effects. Because mobile phones are held close to the body and are used frequently, these devices are potentially the most dangerous sources of electromagnetic radiation that the average person possesses.

Frequency: The fields must vary with time, e.g. those from alternating currents, if they are to have biological effects. Extremely low frequencies (ELF) such as those from power-lines and domestic appliances are more potent than higher frequencies. There is usually little or no biological response to the much higher frequencies of radio waves, unless they are pulsed or amplitude modulated at a biologically active lower frequency (i.e. when the radio signal strength rises and falls in time with the lower frequency). Regular GSM mobile phones and PDAs emit both pulsed radio waves (from the antenna) and ELF (from the battery circuits), and are especially dangerous. So how do these non-thermal effects electromagnetic fields arise?

Weak electromagnetic fields release calcium from cell membranes

The first clue came from Suzanne Bawin, Leonard Kaczmarek and Ross Adey (Bawin et al. 1975), at the University of California. They found that exposing brain tissue to weak VHF radio signals modulated at 16Hz (16 cycles per second) released calcium ions (electrically charged calcium atoms) bound to the surfaces of its cells. Carl Blackman at the U.S. Environmental Protection Agency in North Carolina followed this up with a whole series of experiments testing different field-strengths and frequencies (Blackman et al. 1982) and came to the surprising conclusion that weak fields were often more effective than strong ones. The mechanism was unknown at the time and it was thought to be a trivial scientific curiosity, but as we will see, it has huge significance for us all.

The loss of calcium makes cell membranes leak

Calcium ions bound to the surfaces of cell membranes are important in maintaining their stability. They help hold together the phospholipid molecules that are an essential part of their make-up (see Ha 2001 for a theoretical treatment). Without these ions, cell membranes are weakened and are more likely to tear under the stresses and strains imposed by the moving cell contents (these membranes are only two molecules thick!). Although the resulting holes are normally self-healing they still increase leakage while they are open and this can explain the bulk of the known biological effects of weak electromagnetic fields.

Membrane leakage damages DNA

Leaks in the membranes surrounding lysosomes (tiny particles in living cells that recycle waste) can release digestive enzymes, including DNAase (an enzyme that destroys DNA). This explains the serious damage done to the DNA in cells by mobile phone signals. Panagopoulos et al. (2007) showed that exposing adult Drosophila melanogaster (an insect widely used in genetic experiments) to a mobile phone signal for just six minutes a day for six days broke into fragments the DNA in the cells that give rise to their eggs and half of the eggs died. Diem et al. (2005) also found significant DNA fragmentation after exposing cultured rat and human cells for 16 hours to a simulated mobile phone signal. See also the 'Reflex Project' in an on-line brochure entitled *Health and Electromagnetic Fields* published by the European Commission. You can find it at http://tinyurl.com/yxy4ld. It shows that exposing human cells for 24 hours to simulated mobile phone signals gave DNA fragmentation similar to that due to the gamma rays from a radioactive isotope! (Gamma rays also make lysosome membranes leak.)

DNA damage may cause cancer

There have been many studies suggesting that exposure to weak electromagnetic fields is associated with a small but significant increase in the risk of getting cancer (Wilson et al. 1990). This could be caused by gene mutations resulting from DNA damage. A gene is a section of DNA containing the information needed to make a particular protein or enzyme. There is also a section that can turn the gene on or off in response to outside signals. The growth of an organism from a fertilised egg involves a hugely complex pattern of switching genes on and off that regulates growth, cell division and differentiation into specific tissues. DNA damage can sometimes give unregulated growth to form tumours. However, the effect may not be immediate. Cancer following exposure to chemical carcinogens such as asbestos may take many years to become rampant. The affected cells seem to go through several stages of ever-increasing genetic and molecular anarchy before they finally reach the point of unstoppable growth and division. When assessing any carcinogenic effects of electromagnetic exposure, we must bear in mind that there may be a similar delay. It may be some years before we know the full carcinogenic effects of the recent explosive growth in the use of mobile phones.

DNA damage reduces fertility

The biological effects of electromagnetically induced DNA fragmentation may not be immediately obvious in the affected cells, since fragments of broken DNA can be rejoined and damaged chromosomes (elongated protein structures that carry the DNA) can be reconstituted. However, there is no guarantee that they will be rejoined exactly as they were. Pieces may be left out (deletions) joined in backwards (inversions) swapped between different parts of the chromosome (translocations) or even attached to the wrong chromosome. In most cases, the new arrangement will work for a while if most of the genes are still present and any metabolic deficiencies can often be made good by the surrounding cells. However, things go badly wrong when it comes to meiosis, which is the process that halves the number of chromosomes during the formation of eggs and sperm.

During meiosis, the chromosomes line up in pairs (one from each original parent) along their entire length so that corresponding parts are adjacent and can be exchanged (this gives each of the daughter cells a unique combination of genes). However, if the arrangement of their genes has been altered by electromagnetic exposure, they cannot align properly and the chromosomes may even tie themselves in knots in the attempt. Such malformed pairs are usually torn apart unequally in the later stages of meiosis so that the eggs or sperm have an incomplete or unbalanced set of genes, may not function properly and so reduce fertility. There is evidence from several independent studies in Australia, Hungary and the United States that this is already occurring. Heavy mobile phone use appears to reduce both the quantity and viability of sperm. The results for the most recent study by Dr Ashok Agarwal and co-workers at the Cleveland Lerner College of Medicine can be seen at http://tinyurl.com/28rm6n. They found that using a mobile phone for more than four hours a day was associated with a reduction in sperm viability and mobility of around 25 percent. The statistical probability of these results being due to chance errors was one in a thousand. There is every reason to believe that human eggs may be similarly affected, but since they are formed in the embryo before the baby is born, the damage will be done during pregnancy but will not become apparent until the child reaches puberty.

There may also be permanent genetic damage

Believe it or not, the electromagnetically induced loss of fertility is the *good news* since it means that badly damaged embryos are less likely to be conceived. The *bad news* is that any damaged genes needed for embryo development but not for normal egg or sperm function will not be weeded out in this way. They can still find their way into the foetus and cause permanent genetic damage. The effect may not be apparent in the first generation since a non-functioning gene from one parent can often be offset if the other parent provides a good version of the same gene. In fact, serious trouble may not arise for many generations until by chance two faulty versions of the same gene end up in the same foetus. What happens then depends on the gene concerned, but it is unlikely to be beneficial and may be lethal.

The overall conclusion is that the genetic damage from exposure to electromagnetic radiation can have an almost immediate effect on fertility, but damage to the offspring may take several generations to show up. If we do nothing to limit our exposure to electromagnetic radiation, we can anticipate a slow decline in the viability of the human genome for many generations to come. It is ironic that having only just discovered the human genome, we have already set about systematically destroying it.

Effects on metabolism

Another major effect of electromagnetic radiation is the leakage of *free* calcium ions, either through the cells' external membranes or those surrounding internal 'calcium stores'. This can have dramatic effects on many aspects of metabolism and explains most of the mysterious but well-documented physiological effects of electromagnetic fields. These include stimulations of growth, an increased risk of cancer, symptoms suffered by electrosensitive humans and why using a mobile phone while driving makes you four times more likely to have an accident.

How calcium controls metabolism

Apart from its role in maintaining membrane stability, the calcium concentration actually inside cells controls the rate of many metabolic processes, including the activity of many enzyme systems and the expression of genes. The concentration of calcium ions in the cytosol (the main part of the cell) is normally kept about a thousand times lower than that outside by metabolically-driven ion pumps in its membranes. Many metabolic processes are then regulated by letting small amounts of calcium into the cytosol when needed. This is normally under very close metabolic control so that everything works at the right time and speed. However, when electromagnetic exposure increases membrane leakiness, unregulated amounts of extra calcium can flood in. Just what happens then depends on how much gets in and what the cells are currently programmed to do. If they are growing, the rate of growth may be increased. If they are repairing themselves after injury, the rate of healing may be increased but if there is a mutant precancerous cell present, it may promote its growth into a tumour.

Calcium leakage and brain function

Normal brain function in humans depends on the orderly transmission of signals through a mass of about 100 billion *neurones*. Neurones are typically highly branched nerve cells. They usually have one long branch (the *axon*), which carries electrical signals as *action potentials* (nerve impulses) to or from other parts of the body or between relatively distant parts of the brain (a nerve contains many axons bundled together). The shorter branches communicate with other neurones where their ends are adjacent at *synapses*. They transmit information across the synapses using a range of *neurotransmitters*, which are chemicals secreted by one neurone and detected by the other. The exact patterns of transmission through this network of neurones are horrendously complex and determine our thoughts and virtually everything we do.

Calcium plays an essential role in this because a small amount of calcium must enter the neurone every time before it can release its neurotransmitters. Without it, the brain would be effectively dead. But what would happen if electromagnetically induced membrane leakage let in too much calcium? One effect would be to increase the background level of calcium in the neurones so that they release their neuro-transmitters sooner. This improves our reaction time to simple stimuli (which has been experimentally proven). However, it can also trigger the spontaneous release of neurotransmitters to transmit spurious signals have no right to be there. This feeds the brain false information. Similar spurious action potentials may also be triggered in other parts of the neurone if leaks in the membrane temporarily short-circuit the normal voltage between its inside and outside. These unprogrammed action potentials will degrade the signal to noise ratio of the brain and reduce its ability to make accurate judgements.

It is technically difficult to detect these stray action potentials experimentally since they look like random noise in the measuring system and would in any case be swamped by the relatively strong electromagnetic signals used to induce them. However, similar spurious action potentials should be detectable if we removed some of structural calcium from the membrane by some other means. One way to do this is to lower the concentration of calcium ions in the surrounding medium. For example, Matthews (1986) reported that exposing nerve and muscle cells to calcium concentration about 10–20 percent below normal made them significantly more excitable, which fits with our hypothesis.

These findings also explain many of the symptoms of hypocalcemia (alias hypocalcaemia). Hypocalcemia is a medical condition, usually caused by a hormone imbalance, in which the concentration of ionised calcium in the blood is abnormally low. By removing bound calcium from cell membranes, it should (and does) give similar effects to electromagnetism.

Electrosensitivity and hypocalcemia – a possible cure

Symptoms of hypocalcemia include skin disorders, paresthesias (pins and needles, numbness, sensations of burning etc.) fatigue, muscle cramps, cardiac arrhythmia, gastro-intestinal problems and many others. A more comprehensive list can be found at http://tinyurl.com/2dwwps, which corresponds to the website:
www.endotext.org/parathyroid/parathyroid7/parathyroid7.htm.

The symptoms of hypocalcemia are remarkably similar to those of electrosensitivity. If you think you may be electrosensitive, how many of these do you have? If you have any of them, it may be worth having your blood checked for ionised calcium. It is possible that at least some forms of electrosensitivity could be due to the victims having their natural blood calcium levels bordering on hypocalcemia. Electromagnetic exposure would then remove even more calcium from their cell membranes to push them over the edge and give them symptoms of hypocalcemia. If this is correct, conventional treatment for hypocalcaemia may relieve some if not all of these symptoms.

Electromagnetic exposure and motor accidents

Only a small proportion of the population is electrosensitive in that they show obvious symptoms from electromagnetic exposure. However, everyone may affected without being aware of it, e.g. when using a mobile phone. According to the Royal Society for the Prevention of Accidents, you are four times more likely to have an accident if you use a mobile phone while driving. This is not due to holding the phone since using a hands-free type makes no difference. It is also not due to the distraction of holding a conversation, since talking to a passenger does not have the same effect. This leads us to the conclusion that the electromagnetic radiation from the phone is the most likely culprit.

This fits with the notion that spurious action potentials triggered by electromagnetic radiation creates a sort of 'mental fog' of false information that makes it harder for the brain to recognise weak but real stimuli. For example, a driver using a mobile phone may still see the road ahead using the strong images from the central part of the eye but may be less aware of weaker but still important images coming from the side. He may also be less able to conduct relatively complex tasks such as judging speed and distance in relation to other moving vehicles. This needs a lot of 'computing power' and will therefore be more susceptible to random interference. Although an experienced driver may do much of his driving automatically, his brain still has to do just as much work as if he were still learning; it is just that he is unaware of it. Therefore, an old hand at driving is just as likely to be forced into making a mistake when using a mobile while driving as a novice, so don't imagine you can get away with it just because you have been driving for years. Another important point is that, if this theory is correct, and the electromagnetic signal is mainly to blame, not only is it inadvisable to use a mobile yourself while driving, but your passengers should not use them either since their radiation may still affect *your own* driving.

The theory behind it all

We have seen that weak electromagnetic fields can remove calcium from cell membranes and make them leak. If we theorise about the mechanism, we can explain many of the seemingly weird characteristics of bioelectromagnetic responses. These include why weak fields can be more effective than strong ones, why low frequencies are more potent, why pulses do more damage than sine waves and what is special about 16Hz. The following hypothesis was proposed by Goldsworthy (2006).

The role of eddy currents

Before they can give biological effects, the electromagnetic fields must generate electrical 'eddy currents' flowing in and around the cells or tissues. Both the electrical and magnetic components of the fields can induce them and they tend to follow low impedance pathways. These can be quite extensive; for example in the human body, the blood system forms an excellent low resistance pathway for DC and low frequency AC. It is an all-pervading system of tubes filled with a highly conductive salty fluid. Even ordinary tissues carry signals well *at high frequencies* since they cross membranes easily via their capacitance. In effect, the whole body can act as an efficient antenna to pick up electromagnetic radiation. If you need convincing, try a simple experiment. Tune in a portable radio to a weak station and see by how much you can improve reception by simply grasping the antenna. There is little doubt that signals transmitted by a mobile phone, even if it is a hands-free type, will reach all parts of the body, including the sex organs.

How calcium is released

The membrane: Most biological membranes are negatively charged, which makes them attract and adsorb positive ions. However, these ions are not stuck permanently to the membrane but are in dynamic equilibrium with the free ions in the environment. The relative amounts of each kind of ion attached at any one time depends mainly on its availability in the surroundings, the number of positive charges it carries and its chemical affinity for the membrane. Calcium normally predominates since it has a double positive charge that binds it firmly to the negative membrane. Potassium is also important since, despite having only one charge, its sheer abundance ensures it a good representation (potassium is by far the most abundant positive ion in virtually all living cells and outnumbers calcium by about ten thousand to one in the cytosol).

The signal: When an alternating electrical field from an eddy current hits a membrane, it will tug the bound positive ions away during the negative half-cycle and drive them back in the positive half-cycle. If the field is weak, strongly charged ions (such as calcium with its double charge) will be preferentially dislodged. Potassium (which has only one charge) will be less attracted by the field and mostly stay in position. Also, the less affected free potassium will tend to replace the lost calcium. In this way, weak fields increase the proportion of potassium ions bound to the membrane, and release the surplus calcium into the surroundings.

Why there are amplitude windows

The main effect, electromagnetic treatment is to change the normal chemical equilibrium between bound calcium and potassium in favour of potassium. Even very weak fields should have at least some effect. This effect should increase with increasing field-strength, but only up to a point. If the field were strong enough to dislodge large quantities of potassium too, there will be less discrimination in favour of calcium. This gives an *amplitude window* for the *selective* release of calcium, above and below which there is little or no observable effect.

The field strength corresponding to the amplitude window may vary with the ease with which eddy currents are induced and the nature and physiological condition of the tissue. There may also be more than one in any given tissue. Blackman et al. (1982) discovered at least two for brain slices, perhaps because the brain contains two main types of cell; the neurones and the glial cells, each of which have different membrane compositions.

Why low frequencies and pulses work better

The hypothesis also explains why only frequencies from the low end of the spectrum give biological effects and why pulses and square waves are more effective than sine waves. Only if the frequency is low will the calcium ions have time to be pulled clear of the membrane and replaced by potassium ions before the field reverses and drives them back. Pulses and square waves work best because they give very rapid changes in voltage that catapult the calcium ions well away from the membrane and then allow more time for potassium to fill the vacated sites. Sine waves are smoother, spend less time at maximum voltage, and so allow less time for ion exchange.

Frequency windows

The hypothesis also explains the curiosity that some frequencies are especially effective, with 16Hz being the most obvious. This is because 16Hz is the ion cyclotron resonance frequency for potassium in the Earth's magnetic field (see Box). When exposed to an electromagnetic field at this frequency, potassium ions resonate, absorb the field's energy and convert it to energy of motion. This increases their ability to replace calcium on cell membranes. Although the extra energy gained by each potassium ion may be small, the fact that there are about ten thousand of them competing with just one calcium ion for each place on the membrane means that even a slight increase in their energies due to resonance will have a significant effect.

Ion Cyclotron Resonance

Abraham Liboff, in the mid 1980s, developed the idea that the frequency windows for the biological effects of electromagnetic fields were in some way due to ion cyclotron resonance, but he didn't link it to membrane stability (Liboff et al.1990). Ion cyclotron resonance occurs when ions move in a steady magnetic field such as that of the Earth. The field deflects them sideways and they go into orbit around its lines of force at a characteristic 'resonant' frequency, which depends on the charge/mass ratio of the ion and the strength of the steady field. Exposing them to an oscillating electric or a magnetic field at their resonant frequency lets them absorb its energy and they gradually increase the size of their orbits and their energy of motion. The resonant frequency for potassium in the Earth's magnetic field is close to 16Hz. According to my hypothesis, electromagnetic fields at this frequency specifically increase the ability of potassium ions to bombard cell membranes and replace bound calcium. This increases the biological hazards of electromagnetic exposure near 16Hz and has already caused concern about the safety of the TETRA mobile telecommunications system, which transmits pulses at 17.6Hz.

Amplitude modulated and pulsed radio waves also work

Amplitude modulated and pulsed radio waves consist of a high frequency 'carrier' wave whose strength rises and falls in time with a lower frequency signal. This is the basis of AM radio transmissions, where the low frequency signal comes from an audio source. The receiver demodulates the signal to regenerate the audio. Unmodulated carrier waves usually have little or no biological effect, but if modulated at a biologically-active low frequency (such as 16Hz) they give marked effects (Bawin et al. 1975). This has posed problems for scientists trying to work out how living cells could demodulate radio signals to regenerate the low frequency and elicit a biological response.

However, we can now explain it easily. Imagine a child bouncing a ball continuously against the ground. The harder he hits it, the higher it bounces and the greater its average height. The layer of free positive ions that congregate near but are not bound to the negatively charged surface of a cell membrane will behave in the same way. They bounce against the membrane in time with the radio wave, and the average distance of the electrical centre of the layer from the membrane rises and falls with any amplitude modulation. For example, modulating the signal at 16Hz makes the centre of the layer rise and fall at 16Hz. It does not have to move very far at this frequency, since any free potassium ions in the vicinity will resonate, gradually gain energy from the oscillations and become more able to bombard and displace calcium ions bound to the membrane. Non-resonant frequencies need a stronger signal but can give a similar effect.

Continuous waves can also work

This is probably because living cells can introduce their own time variation in field strength. The membrane systems in active living cells are constantly on the move, e.g. from the Brownian motion of membrane-bound particles (a purely physical process due to molecular bombardment) and physiological processes such as their active transport. This exposes any given section of their membranes to a full frontal attack by the field in one orientation followed by a much quieter period if it rotates through 90 degrees and receives the signal edge-on. This means that it experiences what looks (to it) like a time-varying field and may therefore give a physiological response even to a constant radio signal. However, because these are random changes and are not sharply pulsed, we might expect them to need stronger fields and/or longer exposure times if they are to give effects. This may explain the unpleasant symptoms experienced by many electrosensitive individuals when using UMTS (3G) handsets or living close to high power TETRA base stations. Although neither signal is pulsed, the sheer proximity of the UMTS handset to the user and the raw power of a nearby TETRA base station may give the necessary signal strength. In addition, the lack of any quiet gaps in the signal increases the net exposure time, which may more than compensate for the lack of pulses.

How calcium loss makes holes in membranes

Cell membranes are made of sheets of fatty materials called phospholipids surrounding islands of protein. The proteins have a variety of metabolic functions, but the main role of the phospholipids is to fill the spaces between them and act as a barrier to prevent leakage. Calcium loss weakens the phospholipid sheet and makes it more likely to leak; but how does it do this?

The membrane phospholipids are long molecules. One end consists of hydrophobic (water hating) hydrocarbon chains. The other end has a negatively charged phosphate group and is hydrophilic (water loving). In a watery medium, they arrange themselves spontaneously to form double-layered membranes with a central core made from their water hating ends. Their water loving phosphate ends face outwards towards the water. The affinity that the central hydrophobic parts have for one another helps hold the membrane together but the negatively charged phosphate groups on the outside repel each other and try to tear it apart. Normally, the membrane is stabilised by positive ions that fit in between the negative phosphate groups, so that they do not repel each other. They act as a kind of cement that helps to hold the membrane together.

However, not all positive ions stabilise the membrane equally well. Calcium ions are particularly good because of their double positive charge, but monovalent potassium, with just one charge, is only mediocre. Therefore, when electromagnetic fields swap membrane-bound calcium for potassium, it weakens the membrane (These membranes are only a hundred thousandth of a millimetre thick) and it becomes more prone to accidental tearing and the formation of transient pores. This happens to some degree all the time, even in stationary artificial membranes (Melikov et al. 2001), but the membranes of living cells are often stressed by the cells' moving contents, so the effects should be much greater. Fortunately, these pores are usually self-healing and the damage to the membrane is not permanent. However, during electromagnetic exposure there will be more tears, slower repair and consequently more overall leakage. The metabolic effects of even a brief period of leakage may be much longer lasting (e.g. if dormant genes are activated) and perhaps (as in the case of DNA damage) permanent.

Defence mechanisms

Calcium pumps: Cells have to be able to pump out any extra calcium that has entered their cytosols to reset the low cytosolic calcium level every time it is disturbed by a programmed calcium influx. They should therefore be able to respond to unprogrammed calcium influx due to electromagnetic exposure. This should minimise any unwanted metabolic effects, but the scope to do this is limited. If it were too effective, it would also prevent legitimate cell signalling.

Gap junction closure: If calcium extrusion fails and there is a large rise in internal calcium, it triggers the isolation of the cell concerned by the closure of its gap junctions (tiny strands of cytoplasm that normally connect adjacent cells) (Alberts et al. 2002). This also limits the flow of eddy currents through the tissue and so reduces the effects of radiation.

Heat shock proteins: These were first discovered after exposing cells to heat, but they are also produced in response to a wide variety of other stresses, including weak electromagnetic fields. They are normally produced within minutes of the onset of the stress and combine with the cell's enzymes to protect them from damage and shut down non-essential metabolism (the equivalent of running a computer in 'safe mode'). When the production of heat shock proteins is triggered electromagnetically it needs 100 million million times less energy than when triggered by heat, so the effect is truly non thermal (Blank & Goodman 2000). Their production in response to electromagnetic fields is activated by special base sequences (the nCTCTn motif) in the DNA of their genes. When exposed to electromagnetic fields, they initiate the gene's transcription to form RNA, which is the first stage in the synthesis of the protein (Lin et al. 2001).

As we can see, there are several defence mechanisms against damage by electromagnetic fields and there may be more we do not know about. They probably evolved in response to natural electromagnetic fields such as those generated by thunderstorms but are now having their work cut out to respond to the continuous and all-pervading fields associated with modern living. How well they perform will depend on many factors, including environmental conditions, the physiological condition of the cells and how much energy they have to spare. Consequently, they do not always succeed. When the defences fail, we may get visible symptoms from the radiation, but when they succeed, there may be little obvious effect.

The power and mobile phone companies have seized upon this characteristic variability to discredit work on the non-thermal effects of electromagnetic fields as being due to the experimental error. Nothing could be further from the truth. Many of these experiments are highly reproducible, especially the fundamental and all-important ones on the effects of the radiation on the release of calcium from cell membranes. Secondary effects further down the line may be less reproducible since they are more likely to be mitigated by the intervention of cellular defence mechanisms. Therefore, we cannot expect rigidly reproducible results in all circumstances any more than we can expect everyone to experience exactly the same side effects from taking a medicinal drug. However, that does not mean that they can be safely ignored!

Conclusion

In the latter part of this article, I have explained how weak electromagnetic fields can interact with cell membranes to weaken them and make them more permeable. As with all theories, it will be subject to modification and refinement as time goes by, but some facts are already inescapable. There is undeniable experimental proof that weak electromagnetic fields can remove bound calcium ions from cell membranes. There is also no doubt that bound calcium ions are essential for the stability of these membranes. Consequently, their loss will increase temporary pore formation under the mechanical stresses from pressure differences within the cell and abrasion by its moving contents. This very simple conclusion can account for virtually all of the known biological effects of electromagnetic fields, including changes in metabolism, the promotion of cancer, genetic damage, loss of fertility, deleterious effects on brain function and the unpleasant symptoms experienced by electrosensitive individuals.

However, it seems possible that at least some cases electrosensitivity could be due to low levels of ionised calcium in the blood exacerbating the electromagnetic effects. If so, it may be possible to relieve some or all of the symptoms by conventional treatment for hypocalcemia.

Footnote

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