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Neurological effects of radiofrequency radiation

Bruce Hocking[1] **and R. Westerman**[2]

Background The health effects of radiofrequency radiation (RFR) and the adequacy of the safety standards are a subject of debate. One source of human data is case reports regarding peripheral neurological effects of RFR, mainly noxious sensations or dysaesthesiae.

Aim To investigate health effects, neurophysiological mechanisms and safety levels for RFR.

Methods We conducted a literature search for case reports and case series associated with mobile phone technology as well as other RFR sources using specific search terms on PubMed.

Results We identified 11 original articles detailing case reports or case series and matching the search criteria. Five of the identified papers were written by at least one of the authors (B.H. or R.W.).

Conclusions Cases have arisen after exposure to much of the radiofrequency range. In some cases, symptoms are transitory but lasting in others. After very high exposures, nerves may be grossly injured. After lower exposures, which may result in dysaesthesia, ordinary nerve conduction studies find no abnormality but current perception threshold studies have found abnormalities. Only a small proportion of similarly exposed people develop symptoms. The role of modulations needs clarification. Some of these observations are not consistent with the prevailing hypothesis that all health effects of RFR arise from thermal mechanisms.

Key words Dysaesthesia; mobile phones; neurological effects; radiofrequency radiation.

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Introduction

Most safety standards for radiofrequency radiation (RFR) exposure (3 kHz–300 GHz) are based on either the avoidance of (i) heating effect sufficient to harm tissue due to frequencies >10 MHz or (ii) electrostimulatory effects of frequencies <10 MHz [1,2]. The 'basic restrictions' of the safety standard are based on RFR energy deposition into tissue, expressed as W/kg (watts per kilogram of tissue). On the basis of no consistent health effects having been observed at exposures <4 W/kg, and allowing a 10-fold safety factor, exposure standards are based on limiting exposures to <0.4 W/kg for occupational exposures. A further safety factor of 5 is used to protect the public to give a whole-body exposure limit of 0.08 W/kg. These data are then translated into 'reference levels', i.e. exposure levels expressed in mW/cm^2 (or V/m or A/m) for compliance purposes, e.g. 1 mW/cm^2 for occupational, or 0.2 mW/cm^2 for public, exposures at 300 MHz. The underlying assumptions are that no health effects will occur other than ones with a thermal or electrostimulatory basis, and that RFR does not cause effects due to other means.

Empirical confirmation of the hypothesis that no effects will occur in humans exposed below the safety levels and/or from other mechanisms than heating or electrostimulation has come mainly from epidemiological studies of cancer (which have not found clear evidence of a harmful effect). Another source of data is case reports, of which there have been several regarding peripheral neurological effects (dysaesthesia). These are examined in

[1]9 Tyrone Street, Camberwell, Victoria 3124, Australia.

[2]Caulfield General Medical Centre, 260 Kooyong Road, Caulfield South, Victoria 3162, Australia.

Correspondence to: Bruce Hocking, 9 Tyrone Street, Camberwell, Victoria 3124, Australia. e-mail: bruhoc@connexus.net.au

this paper in order to provide insights into neurophysiological mechanisms and hence safety levels. A literature search was conducted on PubMed using combinations of terms such as 'radiofrequency and nerve' or 'microwave and dysaesthesia', and 'related articles' applied to one of our own papers [3]. The search found few references, and most of the paper uses articles we have sighted over years of studying this topic.

The first three case reports are presented in the context of our ongoing research into the health effects of mobile phones. Then several other case reports, relating to other RFR sources, are described and their implications are discussed.

Case reports

Mobile phone technology

Hocking and Westerman have reported various cases of dysaesthesia associated with mobile phones and base station antennae.

Mobile phones

Hocking [3] reported a case series of 40 people who complained of symptoms associated with use of a mobile phone. A burning sensation or dull ache (quite distinct from an ordinary headache) was felt ipsilateral to the side of use of the phone. It occurred within minutes after use and lasted for minutes or hours. Some cases also reported visual symptoms or not thinking clearly (like being 'hung over'). The mechanism was speculated to be neurological. Subsequently, Hocking and Westerman [4] reported a case of a 72-year-old businessman who had onset of a persistent 'bruised' feeling on the scalp after extensive use of a mobile phone. Neurological investigation found no medical cause. On examination by us 1 year later, he had altered sensation to cotton wool on the scalp on the affected side. On current perception threshold testing [5,6], changes were found for the C3 and trigeminal nerve distributions in the area of his symptoms.

Hocking and Westerman [7] have recently studied a 34-year-old journalist who complained of occipital pain on using her mobile phone. She agreed to a provocation study in which her phone was wrapped in thin polystyrene to avoid heating effects, and she spoke into the phone until symptoms occurred (after ~7 min). Current perception threshold testing showed marked changes in the nerves of the affected area compared with the opposite side and to her pre-exposure values.

Antennae [8]

A 31-year-old rigger was accidentally exposed to his left face from an 870 MHz Code Division Multiple Access (CDMA) panel antenna which was supposed to be off. He worked for ~2 h before feeling unwell when the antenna was recognized to be operating at low power. He developed a headache and blurred vision. When seen the next day, he had a smaller left pupil and altered sensation to cotton wool on his left forehead. Current perception threshold testing found abnormalities of the C-fibres in the left ophthalmic division of the trigeminal nerve, which was again abnormal on testing after 1 month, but had returned to normal when tested 6 months later. The exposure to the head was reconstructed and measured to be 0.01 mW/cm^2, which is below the whole-body occupational exposure standard of 1 mW/cm^2 and similar to that from a mobile phone.

The cases show that neurological effects in mobile phone users may arise from the RFR *per se*, independently of the phone and its alleged affects, such as heating of tissues or position of the head, causing compression neuropathy.

Other RFR exposures

There have been many reports of RFR exposures causing peripheral neurological effects. Reports are presented in order across the RF spectrum where the frequency was stated.

Kolmodin-Hedman *et al.* [9] studied 113 RFR welders (25–30 MHz). The exposures varied, but >50% of measurements of the machines were in excess of the Swedish ceiling exposure level of 25 mW/cm^2. They found 40% of the welders, but only 22% of 23 non-exposed controls who were matched for the manual manipulative work (which could cause compression neuropathies), had symptoms of dysaesthesia. Two-point discrimination was significantly diminished in welders (39/113) compared with controls (1/23). Nerve conduction studies did not find a significant difference in abnormalities (possibly due to carpal tunnel syndrome) between the 38 symptomatic welders (12/38) and the controls (5/23). This study shows that the exposures caused symptoms not detectable on ordinary nerve conduction tests in 26/38 RFR welders.

Schilling has produced two reports of several cases of RFR overexposure [10,11]. Some of the cases have had neurological effects of the central, peripheral and autonomic nervous systems.

Schilling [11] reported a 48-year-old rigger (case X, also examined by B.H.) who was working for some days on a mast in close proximity to a steel cable that was later found to be re-radiating very high frequency (VHF) broadcast radiowaves, causing exposures of 20–150 V/m. After a few days he developed 'flu-like symptoms, headache and symptoms on the right side of his body, which had been close to the cable. He developed testicular and right loin pains (referred pain), and a fuzzy sensation over his right cheek, with loss of sensation on testing. He became progressively lethargic and forgetful. He has not improved over 3 years. Neurological assessment found no medical basis. A workmate with similar exposures also developed symptoms (case Y).

Schilling [10] also described three men overexposed to ultra high frequency (UHF) TV, who have had persistent headaches, fatigue and dysaesthesiae, but no clinical abnormalities on investigation.

Scott *et al.* [12] described 10/200 (5%) patients who were receiving 915 MHz hyperthermia treatment in association with ionizing radiation for superficial cancers, and had developed dysaesthesiae in adjacent nerves. Case 2 was a 68-year-old male with nasopharyngeal cancer and a metastasis in a cervical lymph node. He was treated using a 915 MHz (any modulations were not stated) applicator to the neck, and the lesion was heated. He felt shock-like sensations in his posterior upper arm and jaw in the distribution of the mandibular nerve (which was ~3 cm away from the treated area). The sensation occurred earlier in the treatment period of successive treatments and recurred after power interruption to measure the temperature. The effect saturated at the lowest available applied power of 14 mW/cm^2, which would be slightly less intense at 3 cm distant. Scott *et al.* considered that the 10 patients had a syndrome of non-specific burning, tingling and numbness in a specific nerve. The effect was patient-specific, occurring in over two-thirds of the nominal 10–12 treatment sessions of those affected, but the large majority of patients were unaffected. The symptoms saturated at the minimal power density available from the applicator (14 mW/cm^2). The applicator arrangement led to considerable beam scatter to adjacent tissues; surgical clips were not present. Once the symptoms developed, they were associated with the application of power without a time lag, and ceased at the instant of power removal. The authors concluded the symptoms were a 'direct result of the microwave field and not a thermal effect' (when a time lag due to thermal inertia would be expected). However, a thermal effect cannot be excluded.

Reeves [13] has reviewed the medical records of 34 patients seen at USAF clinics after overexposure (~25–2500 mW/cm^2) to RFR between 1973 and 1985. He found little evidence of tissue damage after medical examination and a screen of blood tests, including full blood examination and liver function tests. Some patients developed dysaesthesia, which the author described as 'real', but no abnormality was found on nerve conduction studies. Case 27 was a 44-year-old male who, whilst repairing a power amplifier, found that a coupler had not been properly secured. That night, he developed tingling pains in his hands. Seven months later, he still had slightly impaired tapping and grip of the right hand. Electromyography and nerve conduction studies were normal. He was exposed to ~90 mW/cm^2 for 20 min, but the frequency and modulations are not stated.

Several cases of dysaesthesia have been reported after accidental exposures in faulty microwave ovens (2.45 GHz) [14]. This can result in a very large energy deposition into the hand(s) and adjacent body from the 600 W source. There may be frank injury to nerves, resulting in muscle fibrillation being detected on electromyographic studies, as well as effects on sensory nerves. Marchiori *et al.* [15] reported a 40-year-old cook who put her right hand inside a microwave oven to check if the food was cooked, but, due to a fault, the oven continued to work. She developed dysaesthesia, causalgia and oedema of the hand, and changes in her median nerve were shown on electromyography. She also complained of dysaesthesia of the right face and reduced right eye vision.

Hocking *et al.* [16] reported an overexposure accident in which only minor effects were found. Two men were exposed to up to 4.6 mW/cm^2 of 4.1 GHz continuous wave (CW) from a wave guide for 90 min. When examined 8 days later, apart from hair loss, no significant abnormalities were found.

Discussion

The above case reports and case series provide information regarding the peripheral neurological effects of RFR and give insights into the range of mechanisms involved. The widespread independent reporting of cases from the UK, USA, Australia and Brazil is evidence of the reality of the symptoms. The dysaesthesiae have been reported after exposure to diverse forms of RFR across the spectrum.

Some effects have been transitory, as with hyperthermia treatment [12] and CDMA exposure [8], whereas others have caused lasting effects, such as after VHF exposure [10,11] or after a microwave oven accident [14,15].

High exposure, such as to a hand in a microwave oven, results in frank nerve damage [15]. For lower exposures, abnormalities are often not detected using ordinary nerve conduction studies, but can be detected using the more sensitive current perception threshold techniques [4]. This indicates that the lower exposures have not grossly injured the nerve but have altered its function. In the case of the 10 hyperthermia patients with clear 'on–off' symptoms in response to exposure [12], this is not consistent with a thermal effect, but may reflect an electrostimulatory mechanism at levels of <14 mW/cm^2 or another unknown mechanism. In the case of the rigger with symptoms arising from a mobile phone antenna and the two people with changes after use of mobile phones, the exposure was less than the current safety standard [4,7,8]. This indicates that thermal mechanisms are unlikely, or that the sensitivity of some people is not accommodated by the standard.

It is noted that only some people exposed to a source develop dysaesthesia. In the case of the hyperthermia cases, only 10/200 (5%) developed dysaesthesia, the two men exposed to 4.1 GHz (CW) for 90 min did not, and obviously only a small fraction of mobile phone users experience symptoms. This suggests either a specific sensitivity of some people and/or a few people who are at the extreme end of a normal distribution of sensitivity develop symptoms.

The importance of modulations in causing effects at low levels of exposure is unclear. Microwave ovens are unmodulated, and their effect at high exposure is consistent with thermal mechanisms. It is not known whether the cancer hyperthermia treatment of Scott *et al.* [12] (915 MHz) was modulated, but this is often the case. The absence of effect in the two men exposed to 4.6 mW/cm^2 of 4.1 GHz, which was known to be unmodulated [16], may be related to this lack of modulation.

Some of these observations confirm current views of RFR mechanisms such as thermal effects from microwave ovens, but others raise questions about our current understanding of health effects of RFR. The effect on nerve tissue to alter its function reversibly rather than destroy it, as with the provocation study [7], is not consistent with a simple thermal mechanism. In the hyperthermia treatment cases exposed to 915 MHz [12], once the symptoms developed, they were associated with the application of power without a time lag, and ceased at the instant of power removal. The authors concluded that the symptoms were a 'direct result of the microwave field and not a thermal effect', when a time lag due to thermal inertia would be expected. The occurrence of an electrostimulatory effect at these frequencies and power levels is unexpected and raises questions about the underlying neurophysiological mechanism of these effects, such as a channelopathy (defined as a disorder of the cell membrane ion channels), although a contribution from heating cannot be excluded.

There are few studies on nerve conduction in laboratory preparations, and studying dysaesthesia is not possible with animals since they are a subjective phenomena. Chou and Guy [17] found that strong pulsed wave or CW 2.45 GHz radiation was not able to elicit action potentials in isolated frog nerves. Pakhomov *et al.* [18] found that nerve velocities did not change, but potential amplitudes decreased using 915 MHz pulsed waves. Seaman and Wachtel [19] observed increased firing rates of *Aplysia* (sea snail) ganglia exposed to 1.5 and 2.5 GHz CW radiation, which further increased when pulsed. Bolashakov and Alekseev [20] found that 900 MHz pulsed wave (but not CW) radiation increased bursts of firing of *Lymnea* (freshwater snail) neurons. The relationship of these observations to dysaesthesia is unknown, but they indicate that RFR may affect neuronal excitability in molluscs.

The occurrence of effects in a few people at levels below current safety standards or from unexplained mechanisms, as in the hyperthermia treatment cases [12], indicates that, while the standards are adequate for most, there is a fraction of people who may develop symptoms. These studies on peripheral nerves are important partly because sometimes the injury is debilitating and partly because they may give insight into possible effects on the central nervous system [21]. They point to the need for further research and caution in the application of the standards.

References

1. International Commission on Non-Ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). *Health Phys* 1998;**74:**494–522.
2. *Australian Standard (Interim) Radiofrequency Fields. Part 1. Maximum Exposure Levels—3 kHz to 300 GHz*. Homebush: Standards Australia, 1998.
3. Hocking B. Preliminary report: symptoms associated with mobile phone use. *Occup Med* 1998;**48:**357–360.
4. Hocking B, Westerman R. Neurological abnormalities associated with mobile phones. *Occup Med* 2000;**50:** 366–368.
5. Masson EA, Veves A, Fernando D, Boulton AJM. Current perception thresholds: a new, quick, and reproducible method for the assessment of peripheral neuropathy in diabetes mellitus. *Diabetologia* 1989;**32:** 724–728.
6. Yaksh TL. Neurologic mechanisms of pain. In Cousins MJ, Bridenbaugh PO, eds. *Neural Blockade in Clinical Anaesthesia and Management of Pain*, 2nd edn. Philadelphia, PA: Lippincott, 1988; 791–844.
7. Hocking B, Westerman R. Neurological changes induced by a mobile phone. *Occup Med* 2002;**52:**413–415.
8. Hocking B, Westerman R. Case report: neurological abnormalities associated with CDMA exposure. *Occup Med* 2001; **51:** 410–413.
9. Kolmodin-Hedman B, Hanson M, Jonsson E, Andersson M, Erikson E. Health problems among operators of plastic welding machines and exposure to radiofrequency electromagnetic fields. *Int Arch Occup Environ Health* 1988;**60:**243–247.
10. Schilling C. Effects of acute exposure to ultra high radio-frequency radiation on three antenna engineers. *Occup Environ Med* 1997;**54:**281–284.
11. Schilling C. Effects of exposure to very high frequency radiofrequency radiation on six antenna engineers in two separate incidents. *Occup Med* 2000;**50:**49–56.
12. Scott RS, Clay L, Storey KV, Johnson RJ. Transient microwave induced neurosensory reactions during superficial hyperthermia treatment. *Int J Radiat Oncol Biol Phys* 1985;**11:**561–566.
13. Reeves GI. Review of extensive workups of 34 patients overexposed to radiofrequency radiation. *Aviat Space Environ Med* 2000;**71:**206–215.
14. *WHO Environmental Health Criteria 137. Electromagnetic Fields 300 Hz–300 GHz*. Geneva: WHO, 1994.

15. Marchiori P, Silva H, Hirala M, Lino A, Scoff M. Acute mutiple mononeuropathy after accidental exposure to oven microwave. *Occup Med* 1995;**45:**276–277.
16. Hocking B, Joyner K, Fleming R. Health aspects of radio frequency radiation accidents. Part 7. *J Microwave Power EME* 1988;**23:**67–74.
17. Chou CK, Guy A. Effects of electromagnetic fields on isolated nerve and muscle preparations. *IEEE Trans Microwave Theory Technol* 1978;**141:**26.
18. Pakhomov A, Dubovick B, Kilupayer V, *et al.* Search for microwave-sensitive structures and functions in the nervous system. Paper presented at the Fourteenth Annual IEEE/EMBS, Paris, 1992, 297.
19. Seaman R, Wachtel H. Slow and rapid responses to CW and pulsed microwave radiation by individual *Aplysia* pacemakers. *J Microwave Power* 1978;**13:**77–85.
20. Bolshakov M, Alekseev S. Bursting responses of *Lymnea* neurons to microwave radiation. *Bioelectromagnetics* 1992; **13:**119–126.
21. Preece A, Iwi G, Davies-Smith A, *et al.* Effect of a 915-MHz simulated mobile phone signal on cognitive function in man. *Int J Radiat Biol* 1999;**75:**447–456.