Effects of electromagnetic field exposure on the heart: a systematic review

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REVIEW

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Exposure to extremely-low-frequency electromagnetic fields and radiofrequency radiation: cardiovascular effects in humans

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Abstract Cardiovascular changes in humans exposed to nonionizing radiation [including extremely-low-frequency electromagnetic fields (ELF EMFs) and radiofrequency radiation (RFR)] are reviewed. Both acute and long-term effects have been investigated. In general, if heating does not occur during exposure, current flow appears to be necessary for major cardiovascular effects to ensue, such as those due to electric shock. Whereas most studies have revealed no acute effect of static or time-varying ELF EMFs on the blood pressure, heart rate, or electrocardiogram waveform, others have reported subtle effects on the heart rate. The possible health consequences of these results are unknown. Regarding long-term effects of ELF EMFs, reports from the former Soviet Union in the early 1960s indicated arrhythmias and tachycardia in high-voltage-switchyard workers. Subsequent studies in Western countries, however, did not confirm these findings. These studies are limited by uncertainties regarding exposure durations and appropriate control groups. Investigations of acute cardiovascular changes in humans purposely exposed to RFR have been limited to studies of magnetic resonance imaging (which, in addition to RFR, involves static and time-varying magnetic fields). It has been concluded that such exposures, as presently performed, are not likely to cause adverse cardiovascular effects. Reports of hypertension in workers potentially exposed to high levels of RFR during accidents are considered to be incidental (due to anxiety and posttraumatic stress). Soviet investigators have also indicated that long-term RFR exposure may result in hypotension and bradycardia or tachycardia. Other researchers, however, have been incapable of replicating these results, and some scientists have attributed the effects to chance variations and mishandling of data. In summary, studies have not yielded any obvious cardiovascular-related hazards of acute or long-term exposures to ELF EMFs or RFR at levels below current exposure standards.

Key words Electromagnetics · Electromagnetic fields · Microwaves · Heart rate · Blood pressure

Introduction

Electromagnetic fields (EMFs, consisting of separate electric and magnetic components) comprise a broad spectrum of nonionizing radiation ranging from static fields to microwave frequencies. Research on biological effects may be categorized mainly into two groups: extremely-low-frequency (ELF) EMFs (essentially 50 or 60 Hz) and radiofrequency radiation (RFR, 3 kHz to 300 GHz). The electric and magnetic fields are more strongly coupled to one another at higher frequencies. Knave (1994) summarized the types of exposure to electric and magnetic fields that are present in today's world. Both residential exposures (of people living in the vicinity of transmission and distribution lines) and occupational exposures (of workers in jobs associated with EMF environments) are possible.

Recently suggested threshold limit values for exposure to ELF EMFs are a magnetic flux density of 10 mT (100 G) and an electric field of 25 kV/m (Moss and Booher 1994). Guidelines for limits of exposure to RFR range from 0.2 to 10 mW/cm^2 (depending on the wavelength) as suggested by the Institute of Electrical and Electronic Engineers (1992). This work has been used as the basis for other guidelines, including a revised North Atlantic Treaty Organization standardization agreement (Grandolfo 1995).

The views and opinions expressed in this paper are those of the author and do not necessarily state or reflect those of the United States Government

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Most concerns about alleged health effects of EMFs have been related to cancer and reproductive effects (Jauchem and Merritt 1991; Jauchem 1991, 1992, 1993a,b, 1995b). Reports of cardiovascular effects, however, may also be found in the data base of EMF bioeffects.

Cardiovascular changes occurring during heating due to RFR exposure have previously been reviewed (Jauchem and Frei 1992). That review focused on physiological responses in animals and compared these changes with those detected in studies of conventional environmental heating. Polson and Heynick (1992, 1995) also reviewed biological effects, including cardiovascular effects, due to RFR exposure. Another paper (Jauchem 1995a) reviewed studies of cardiovascular responses to RFR exposure in humans.

The purpose of this paper is to review cardiovascular changes in human subjects during exposure to ELF EMFs and to update findings of cardiovascular changes due to RFR exposure. In general, this review does not repeat in any detail the findings of studies mentioned in previous reviews but instead focuses on more recent studies. A few in vivo animal studies are discussed in situations where human-exposure studies are not available (e.g., acute effects of RFR). This paper does not address RFR ablation of heart tissue; this topic has been reviewed elsewhere (e.g., Manolis et al. 1994; Wagshal et al. 1995). [Recently, Simmers et al. (1996) concluded that effects of RFR ablation are exclusively thermally mediated.] In addition, effects on cardiac pacemakers (previously reviewed by Anderson and Kaune 1988; Creasey and Goldberg 1993; Snow et al. 1995) are not addressed herein.

Extremely-low-frequency electromagnetic fields: acute effects

In general, during exposure to EMFs, current flow appears to be necessary for major cardiovascular effects to occur, such as those due to electric shock (e.g., Hocking et al. 1994). Although electric shock would normally require direct electrical contact with the body, shock could conceivably occur if the body were exposed to very strong alternating electric or magnetic fields (Foster 1992). Subtle effects have been reported in other situations of low-level exposure. Studies of ELF EMFs and the cardiovascular system have generally focused on acute rather than long-term effects.

Electrocardiogram changes

An increase in the amplitude of the T-wave signal in the rat electrocardiogram (EKG) has been observed during exposure to magnetic fields (Gaffey and Tenforde 1981). This change, however, appears to be the result of a superimposed electrical potential generated by aortic blood flow in the presence of the magnetic field. When a stationary, transverse magnetic field is applied, electric currents are induced in the blood, which is a moving, electrically conducting fluid (Sud and Sekhon 1989). Although it has been suggested that a Lorenz force may result (which would tend to impede the movement of blood; Sud and Sekhon 1989), no hazardous effect resulting from this phenomenon has been reported. Significant increases in blood pressure would be expected to occur only during exposure to relatively high fields [e.g., a 10% elevation would require about 8 T (Miller 1987); Kinouchi et al. (1996) predicted that 10- to 15-T fields would reduce blood flow by 5–10%]. No measurable change in blood pressure was associated with the change in T-wave signal seen in the study by Gaffey and Tenforde (1981). The T-wave was affected rather than other components of the EKG, since blood flows through the aorta during this period (when the ventricles are recovering). The aortic voltage thus appeared on the EKG as an enlarged T-wave. Further examination showed that this voltage was unrelated to the electrical activity of the pacemaker area of the heart (Miller 1987).

To report that exposure to a magnetic field alters the EKG and, therefore, can potentially damage the heart would be extremely misleading. The EKG change is simply a reflection of the coincident "magnetohydrodynamic" voltage generated by the blood flow in the presence of the applied magnetic field. Kanal (1992) noted that although these EKG changes are not considered to be clinically significant, their existence should be recognized and should not be confused with signs of patient distress. Radiofrequency interference with the EKG resulting from disruption of the signal transmitted through EKG leads is another issue that has previously been discussed (Damji et al. 1988).

Silny (1981) observed over 100 persons exposed to time-varying magnetic fields (5 Hz to 1 kHz, less than 100 mT, 80 kA/m) and found no effect on the EKG. Nagano et al. (1991) found no change in the EKG or heart rate in humans exposed to strong magnetic fields (up to 1.3 T) applied percutaneously to the area of the phrenic nerve, which produced ventilatory changes. In another study, no significant change in blood pressure or heart rate was reported in humans exposed to magnetic pulses of up to 2.2 T (Chokroverty et al. 1995).

Heart-rate changes: studies with multiple comparisons

For several years, investigators at one laboratory (Midwest Research Institute, Kansas City, Mo.) have studied effects of EMFs on the heart rate in humans. In an initial study of men exposed to 60-Hz electric and magnetic fields (Graham et al. 1987), exposure resulted in a significant decrease in heart rate. Maresh et al. (1988) examined six physiological parameters at five timed sampling points in humans exposed to 60-Hz electric and magnetic fields, with or without exercise (a total of 60 comparisons between sham and 60-Hz-exposed groups). During no-exercise sessions the cardiac interbeat interval was increased at two sampling points when subjects were exposed to 60-Hz fields. There was no other difference between the sham and exposed groups. In another study the investigators found that in general, the change in cardiac interbeat interval was not significantly ($P < 0.05$) different during 60-Hz field exposures as opposed to sham conditions (Graham et al. 1990; Cook et al. 1992). Under very specific circumstances (dependent on the order in which subjects were sham- and field-exposed), however, an increase in the interval was significantly greater during field exposure (an increase of 12%) than during sham exposure (an increase of 7%). In the most recent study (Graham et al. 1994), subjects were exposed at different levels of combined electric and magnetic field strength (low: 6 kV/m, 10 μT; medium: 9 kV/m, 20 μT; high: 12 kV/m, 30 μT). A significantly decreased heart rate was observed in the "medium" group but not in the other groups.

Hughes (1994) pointed out that the studies of Graham et al. did not show striking changes and that the subjects may have been aware of the switching on and off of the EMFs. He suggested that this awareness could be related to the short-lived slowing of the heart rate. In addition, some of the studies involved a large number of multiple comparisons. Without proper statistical correction factors (Westfall and Young 1993), the significance of the results may be questionable. Anderson and Kaune (1988) reviewed some of Graham et al.'s work and remarked: "Although some differences appear to exist between exposed and sham-exposed subjects, particularly in...heart rate, the effects are not consistent across time and lie within the range of normal biological variation." Creasey and Goldberg (1993) also reviewed Graham et al.'s work and did not consider the effects to be a "...cause for concern as adverse health effects." Creasey and Goldberg (1993) added that the effects represent well-documented responses of humans to ELF magnetic fields (in contrast to earlier dramatic but poorly documented reports of effects). Sagan (1992) also noted that the possible health consequences of the results are uncertain. Whittington et al. (1996) pointed out that the decreased heart rate mentioned above has rarely been replicated across different research laboratories. These investigators found no effect of a 50-Hz, 100-μT magnetic field (for several durations) on heart rate or blood pressure.

Other studies and reviews

Gamberale et al. (1989) cited several studies in the non-peer-reviewed literature that reported no change in the circulatory systems of workers potentially exposed to ELF EMFs. Gamberale (1990) reviewed human studies and concluded that exposure of the general public and of workers to ELF EMFs does not constitute a health hazard with respect to acute physiological effects, including those on the cardiovascular system.

Simon (1992) reviewed effects of static magnetic fields on the cardiovascular system and reported that "...on both theoretical and experimental grounds, there seems to be no significant effect of fields to 1.5 T on blood pressure." Tenforde et al. (1983) noted that little cardiovascular stress, if any, would be expected to result from exposure of humans to magnetic fields of up to 1.5 T. This conclusion was based on experiments using monkeys and on theoretical calculations for human exposures. Preliminary results of Jehenson et al. (1988) demonstrated static-field effects on the pulse rates of human subjects. Exposure to a 2-T field resulted in a 17% increase in cardiac cycle length; values returned to preexposure levels within 10 min of exposure. The authors hypothesized an effect on the sinus node that they suggested was probably harmless in healthy subjects. The authors stated that the safety of such an exposure in dysrhythmic patients had not been determined. It appears that the change in cardiac cycle length has not been investigated further (as indicated by a search of the literature in Medline 1988 – May 1996).

Korpinen and Partanen (1994a) reported that exposure to 50-Hz EMFs (up to 10.21 kV/m and 15.43 μT for several hours) did not affect the incidence of extrasystoles or arrhythmias in human subjects. A small decrease in heart rate was seen in a few cases after exposure (Korpinen et al. 1993), but these could have been related to changes in the work load of the subjects. In another study, humans exposed for 60 min to EMFs under a 400-kV power line exhibited no difference in pulse rate, EKG, or blood pressure during autonomic function tests (orthostatic tests, Valsalva maneuver, deep breathing) as compared with responses observed in sham-exposed subjects (Korpinen and Partanen 1994b, 1995). Furthermore, 1-h exposures to fields of < 4.3 kV/m and < 6.6 μT did not affect the diastolic or systolic blood pressure (Korpinen and Partanen 1996).

Modeling magnetic-resonance-imaging exposures

Simunic et al. (1995) used a model to simulate exposure of the human torso to switched magnetic fields that would be present during magnetic resonance imaging (MRI). These researchers calculated the induced current density necessary to exceed the threshold for depolarization of a heart cell. The results showed that stimulation of a heart cell would not occur during exposure to standard conditions used in medicine and industry (1.5 T, gradients with a rise time of 0.3 ms, 10 mT/min). Reilly (1991) noted that "...although existing guidelines on MRI magnetic fields have been adequate to preclude any known biological problems to date, the MRI industry would like to have greater flexibility in developing future designs." For pulsed magnetic stimuli, field-strength thresholds for cardiac effects are much higher than thresholds for neuromuscular effects (Reilly 1991). Thus, violent skeletal muscle contractions would be expected before any cardiac abnormality. This phenomenon has been demonstrated in animal studies by McRobbie and Foster (1985).

A number of studies of effects on the cardiovascular systems of animals have been performed. Many of these, however, have involved exposures to relatively large field strengths and have been performed with current flow present (e.g., Silny 1985 as cited in Anderson and Kaune 1988).

Some of the studies mentioned above are summarized in Table 1. Most of the studies showed no effect. The medical significance of any of the "effects" listed is not readily apparent.

Extremely-low-frequency electromagnetic fields: epidemiology studies of long-term effects

Creasey and Goldberg (1993) noted that reports from the former Soviet Union in the early 1960s indicated arrhythmias and tachycardia in high-voltage-switchyard workers (in fields as high as 26 kV/m). Subsequent studies in Western countries, however, did not confirm these effects (Knave and Floderus 1988). Reports of the use of EMF exposure as therapy for hypertension (e.g., Orlov et al. 1991) have also not been confirmed.

Sazanova (1967) reported lower pulse rates in switchyard workers exposed to 50-Hz fields. Knave et al. (1979) and Stopps and Janischewsky (1979) reported no significant effect on cardiovascular function in male workers occupationally exposed to ELF EMFs. Subjects included workers with more than 5 years of exposure to electric fields from 400-kV power lines. Hauf (1982, 1989) performed tests in which human subjects were exposed to an electric field of 20 kV/m and a magnetic field of 0.3 mT while a current of 500 μA at 50 Hz was passed through the body. There was no significant effect on the heart rate or blood pressure. Other similar studies have been reviewed by Cook et al. (1992). Checcucci (1985) reported no effect of exposure to ELF EMFs (1–4.6 kV/m, 4–15 μT) on the cardiovascular systems of 1200 workers at high-voltage railway substations. In a

Table 1 Summary of studies concerning extremely-low-frequency electromagnetic fields: acute effects

Reference	Field strength	Parameter studied	Effect[a]	Notes
Cook et al. 1992	–	Interbeat interval	+	Dependent on order of sham/exposure
Chokroverty et al. 1995	2.2 T	Heart rate, blood pressure	0	–
Gaffey and Tenforde 1981	–	EKG T-wave amplitude	+	Result of potential generated by blood flow
Graham et al. 1987	–	Heart rate	−	–
Graham et al. 1990	–	Interbeat interval	+	Dependent on order of sham/exposure
Graham et al. 1994	10–30 μT	Heart rate	−	Only at 20 μT
Jehenson et al. 1988	2.0 T	Cardiac cycle length	+	Returned to pre-exposure values in 10 min
Korpinen and Partanen 1994a	15.43 μT	Arrhythmias	0	–
Korpinen and Partanen 1994b	6.6 μT	Heart rate, blood pressure	0	–
Korpinen and Partanen 1995	6.6 μT	Heart rate, blood pressure	0	During autonomic function tests
Korpinen et al. 1993	15.43 μT	Heart rate	−	Changes in work load
Korpinen and Partanen 1996	6.6 μT	Blood pressure	0	–
Maresh et al. 1988	–	Interbeat interval	+	Total of 60 comparisons
Miller 1987	8.0 T	Blood pressure	+	–
Nagano et al. 1991	1.3 T	EKG, heart rate	0	Field applied to area of phrenic nerve
Silny 1981	100 mT	EKG	0	Time-varying fields
Simon 1992	1.5 T	Blood pressure	0	
Simunic et al. 1995	1.5 T	Heart stimulation	0	Predicted by model
Tenforde et al. 1983	1.5 T	Cardiovascular stress	0	–

[a] 0 = No statistically significant effect, + = increase, − = decrease

cross-sectional health survey of 627 railway high-voltage substation workers in Italy, Baroncelli et al. (1986) found no difference in the EKG recorded for the exposed versus control groups.

Savitz and Loomis (1995) found that among electric utility workers, mortality from "diseases of the heart" was lower than anticipated on the basis of general population rates (standardized mortality ratio 0.76). The cause of death was coded according to the United States Health Care Financing Administration (1980) and was categorized according to Steenland et al. (1990). The low standard mortality ratio could have been due to a "healthy worker effect" (in which employment selection leads to lower mortality rates as compared with that of the general population). Gurvich et al. (1995) reported no excess of cardiovascular disease in linesmen, substation operators, or maintenance workers exposed to ELF EMFs (voltage as high as 2000 kV/m).

Easterly (1982) developed a model of the cardiovascular system to estimate the potential increase in blood pressure occurring during magnetic-field exposure (see the discussion of magnetohydrodynamic voltage generation above). He concluded that "...an individual's cardiovascular disease risk resulting from exposure to static magnetic fields should not be a serious problem."

Man-made magnetic disturbances and myocardial infarctions: a causal relationship?

Villoresi et al. (1994b) proposed that "...when [a] magnetic field exceeds 0.05 T it leads to real danger connected with development of heart fibrillation and further irreversible changes." Yet, in an article that was cited as being supportive of this statement, Saunders (1989) stated that "...above 1000 mA/m^2 (corresponding to a 50 or 60 Hz field of greater than 500 mT), acute health hazards, such as heart fibrillation, exist." Thus, this potential hazard is related to the induced current flow that would be possible in humans exposed to 10 times the magnetic-field strength listed by Villoresi et al.

Villoresi et al. (1994a,b) reported a large decrease in myocardial infarction rates on Saturdays, Sundays, and public holidays. They remarked that there were greater "...man-made magnetic disturbances" on work days than during weekends. They thus concluded that myocardial infarctions "...could be triggered by man-made magnetic fields." This linkage was made without evidence of a causal relationship; other factors that might be involved (e.g., different work or social habits on week days versus weekends) were not mentioned.

Geomagnetic activity and cardiovascular health

The most prevalent source of magnetic-field exposure for humans is the earth's magnetic field (ranging from 30 to 70 μT), which is much stronger than average fields created by delivery of electricity to homes (commonly 0.1–0.2 μT; Stuchly 1986). Some man-made fields are stronger [e.g., those created in arc welding (Stuchly 1989) and medical applications such as MRI (discussed above)], but exposures in these situations are of much shorter duration.

Although possible correlations between changes in geomagnetic activity and cardiovascular health have been reported, questions have been raised concerning the validity of statistical tests and inadequate allowance for seasonal variations in these studies. Malin and Srivastava (1979) reported a correlation between admissions of cardiac emergency cases and changes in geomagnetic activity. Lipa et al. (1976), however, normalized data to remove weekly and seasonal variations and found no relationship between geomagnetic indices and mortality from myocardial infarction and stroke.

Stoupel et al. (1995b,c) reported a number of findings relating to geomagnetic activity and cardiovascular health. Some aspects were negatively correlated with high levels of geomagnetic activity (e.g., cardiovascular- and stroke-related deaths, pregnancy-induced hypertension), whereas others were positively correlated (e.g., daytime systolic and diastolic blood pressure). The large number of geophysical parameters and categories of death analyzed without correction for multiple statistical comparisons (Westfall and Young 1993) make the results difficult to interpret.

Tyasto et al. (1995) refined the myocardial infarction data of their earlier studies (Villoresi et al. 1994a,b) by analyzing "meteorological and social effects." In this case the myocardial infarction rate was increased slightly (14%) during geomagnetic storms.

Cabanes (1985) pointed out that most studies reporting cardiovascular effects of ELF-EMF exposure are open to criticism. Zagorskaia et al. (1990) noted that "...published data about EMF effects on the cardiovascular system...are often contradictory, probably, because of different estimates of allowable limits recognized in various countries." Anderson and Kaune (1988) reviewed epidemiology studies of ELF EMFs and remarked: "The value of many of these studies has been compromised by one or more of three serious problems: (a) small sample sizes with extremely limited statistical power; (b) failure to obtain quantitative data on levels and durations of exposure; and (c) uncertainty about what constitutes an appropriate control group."

Some of the studies mentioned above are summarized in Table 2. Most of the studies showed no effect. Again, the medical significance of any of the "effects" listed is not readily apparent.

Radiofrequency radiation: acute effects

Cardiovascular effects in animals: relevant studies

Since there have been few studies of acute cardiovascular effects in humans exposed to radiofrequency radiation (RFR), a few experiments conducted using animals are

Table 2 Summary of Studies Concerning Extremely-low-frequency electromagnetic fields: Long-term effects

Reference	Field strength	Parameter studied	Effect[a]	Notes
Baroncelli et al. 1986	–	EKG	0	627 high-voltage substation workers
Checcucci 1985	4.6 kV/m; 15 μT	EKG	0	1200 high-voltage substation workers
Creasy and Goldberg 1993	26 kV/m	Arrhythmias, heart rate	+	Review of 1960s' work
Gurvich et al. 1995	2000 kV/m	Cardiovascular disease	0	–
Hauf 1982, 1989	20 kV/m; 0.3 mT	Heart rate, blood pressure	0	Current of 500 μA through body
Knave et al. 1979	–	Cardiovascular function	0	5 year exposures to 400-kV power lines
Savitz and Loomis 1995	–	Heart-disease mortality	−	In electric utility workers
Sazanova 1967	–	Heart rate	−	–
Stopps and Janischewsky 1979	–	Cardiovascular function	0	5-year exposures to 400-kV power lines
Villoresi et al. 1994a, b	–	Myocardial infarctions	+	On "work days"; no causal relationship

[a] 0 = No statistically significant effect, + = increase, − = decrease

summarized herein. Tachycardia or arrhythmia in isolated frog hearts produced by a direct, "nonthermal" action of pulsed RFR was reported by Frey and Seifert (1968). Other investigators, however, could not confirm this effect (Clapman and Cain 1975; Liu et al. 1976).

As mentioned above, effects of heat-inducing levels of RFR exposure have been reviewed previously. Our laboratory has performed extensive studies of various aspects of cardiovascular responses to high levels of RFR, including effects of body orientation relative to the field (Frei et al. 1989a–c, 1990; Jauchem et al. 1990; Frei and Jauchem 1992), RFR power levels (Jauchem et al. 1984b; Frei et al. 1988), continuous-wave versus pulsed RFR (Jauchem et al. 1983b; Frei et al. 1988, 1989d), anesthesia (Frei and Jauchem 1989; Jauchem and Frei 1991), drug treatments (Jauchem and Frei 1994; Jauchem et al. 1983a,b, 1984a, 1985a,b, 1988, 1995a, 1996a,b), and millimeter-wave exposure (Frei et al. 1995; Ryan et al. 1996). These studies involved the use of the rat as an animal model. Results showed that in general, a greater degree of heating leads to a larger increase in heart rate. Knepton et al. (1983) verified this in conscious rhesus monkeys. Yee et al. (1984, 1988, 1994) found effects of microwaves on the heart rate of isolated frog heart that were thermal in nature. No change in the heart-cell potential or heart rate were found when the temperature was controlled.

MRI of humans

Investigations of cardiovascular changes in humans purposely exposed to RFR have been limited to studies of MRI (which, in addition to RFR, involves static and time-varying magnetic fields). Results obtained by Shellock and Crues (1987) and Schaefer (1992) have been summarized elsewhere (Jauchem 1995a; Shellock 1995). These researchers concluded that exposure to EMFs during MRI, as presently performed, is not likely to cause adverse cardiovascular effects. (For further discussion of magnetic fields during MRI, see Extremely-low-frequency electromagnetic fields: acute effects.)

Accidental exposure

Williams and Webb (1980) reported hypertension in one flight mechanic presumably exposed to RFR at a level of 38 times above the permissible exposure limit. This finding, however, was considered to be incidental; the elevated blood pressure was attributed to anxiety. Forman et al. (1982) reported two cases of hypertension in workers with accidental microwave exposure. The authors postulated that posttraumatic stress was a likely explanation for such cases.

RFR: epidemiology studies of long-term effects

Epidemiology studies of suspected RFR exposure are few in number and have generally been limited in scope. The principal groups studied have been individuals presumably exposed while assigned to the military services or working in particular occupations or industrial settings. Accurate estimates of dose are often difficult to obtain (Silverman 1979).

The first reports that mentioned possible effects of microwave exposure on the cardiovascular system were from the former Soviet Union. Drogichina et al. (1966), Glotova and Sadčikova (1970), and Sadčikova (1974) suggested that exposure to microwaves could directly or indirectly alter the cardiovascular system. Other Soviet investigators indicated that RFR exposure might result in hypotension and bradycardia or tachycardia (Presman and Levitina 1962; Gembitskiy 1972; Subbota 1972). Other researchers, however, have been incapable of replicating these results, and Kaplan et al. (1971) have attributed the changes in heart rate observed by some of the Soviet investigators to chance variations and mishandling of data. Obrosov et al. (1971) reported these changes in volunteer subjects exposed to 2.5-GHz microwaves delivered via a waveguide applicator directed toward the skin surface in the cardiac region. The effects were transient and were associated with sensations of skin pain and warmth, as the skin temperature increased by 1 °C in 10 min. Resnekov (1981) and Kristensen (1989) have pointed out that in general, these studies from the former Soviet Union are difficult to evaluate due to the methodology and terminology used. Gordon (1966) stressed the difficulties of differentiating between effects of microwave irradiation and effects of other environmental factors. According to Barański and Czerski (1976), Gordon (1966) has pointed out that some symptoms in radar operators, including bradycardia, can be attributed to "..peculiar lighting, the necessity of paying attention to the radar screen, the posture during work, noise, or inadequate ventilation." Rayman (1995) reported that although "radiowave sickness" has often been described in Eastern Europe, it has not been demonstrated in the West.

Chiang and Yee (1979) reported subjective complaints of palpitation, bradycardia, hypotension, and S-T depression in "persons exposed to microwaves" (either acutely to less than 0.2 mW/cm^2 or chronically to 0.2–2 mW/cm^2). Djordjević et al. (1979) measured cardiovascular parameters in 322 radar workers (all exposed to pulsed microwaves) and a control group of 220 persons. Neither the incidence of hypertension and cardiomyopathy nor the values of EKG components (P-waves/s; P-Q, QRS, and Q-T intervals; and T-wave voltage) differed between the groups. Robinette et al. (1980) reported that personnel exposed to microwaves showed no increased mortality due to circulatory-system disease. In one study (Burr and Hoiberg 1988), hospitalization rates for diseases of the cardiovascular system did not significantly differ between United States Navy pilots of electronically modified aircraft (with higher exposure to EMFs) and control pilots.

Hamburger et al. (1983) reported an apparently significant association between exposure to shortwave (27-MHz) radiation and heart disease. A task group organized by the World Health Organization and the International Radiation Protection Association has suggested that the reported increased risk "...calls for further studies" (World Health Organization 1993). Heynick and Polson (1984), however, reviewed this study and found that statistical significance was shown only after inappropriate regrouping of subjects, and then for only one medical condition of the ten tested. Thus, the study did not provide strong evidence for an association between shortwave exposure and heart disease. Heynick (1987) also noted that of 90 contingency tables, only 4 showed significance at the 5% level, a finding no better than chance.

Roberts and Michaelson (1985) reviewed epidemiology studies of humans exposed to RFR and concluded that no "identifiably serious" cardiovascular disturbances have been seen as a result of RFR exposure. Hocking et al. (1988) found no change in the blood pressure or EKG of nine male subjects accidentally exposed to 4.1-GHz microwaves; two of the subjects were exposed to 4.6 mW/cm^2 for up to 90 min.

In a case-control study (Tikkanen and Heinonen 1991), maternal exposures to microwave ovens or video-display terminals at work or home were not associated with the risk for cardiovascular malformations. More specifically, exposures during the first trimester of pregnancy were not associated with the risk for atrial or ventricular septal defects (Tikkanen and Heinonen 1992a,b).

Bortkiewicz et al. (1995) reported "...measurable effects in the heart rate variability and blood pressure parameters" in workers at AM broadcasting stations as compared with a control population, but "...none could be assigned clinical significance." Indeed, almost all of the large number of parameters measured [including EKG abnormalities (conduction, rhythm, and repolarization disturbances), heart rate (day, night, and 24-h mean), heartbeat duration, heart-rate variability (low- and high-frequency arrhythmias, low-/high-frequency ratio), blood pressure (systolic and diastolic day, night, and 24-h mean)] did not significantly differ between the RFR-exposed and control groups. Only the day/night ratios for systolic blood pressure and heart rate differed significantly. The authors concluded that a multiyear occupational exposure to RFR of about 0.7- to 1.5-MHz frequency "...cannot be characterized as a considerable risk factor for ischemic heart disease."

Zhao et al. (1994) studied electronics-industry workers who were reported to be exposed (6 h/day, 6 days/week, for 1 year) to RFR at frequencies of less than 30 MHz. Subjects were divided into two groups: one presumably exposed to ≥ 100 V/m and another, to < 100 V/m. A "control" group of "mechanical workers" was included for comparison. The investigators stated that "...statistical evaluation of all data was carried out" but no details were described. Incidences of "cardiovascular complaints" (including palpitation and "stuffiness") were greater in the two exposure groups than in the control group. The prevalence of incomplete right-bundle-branch block was greater in the high-exposure group than in the other two groups. The lack of details regarding exposure assessment and statistics renders the study difficult to interpret.

Nikolova et al. (1995) compared the cardiac intervals and systolic and diastolic blood pressure of workers at a television relay station with values recorded for a control group whose working conditions involved no RFR exposure. These investigators reported no evidence of significant changes in these parameters.

Stoupel et al. (1995a) reported that mortality due to myocardial infarction was positively correlated with radiowave propagation from the sun during hours of maximal solar activity. As in the aforementioned studies by this group (see Geomagnetic activity and cardiovascular health), however, the large number of geophysical parameters and categories of death analyzed without correction for multiple statistical comparisons make the results difficult to interpret.

Emerging microwave-exposure systems – high-peak-power and ultra-wideband systems

Recent developments in electromagnetic technology have resulted in exposure sources capable of generating pulses with relatively short pulse widths. Due to the short pulse width and low pulse frequency (relative to more conventional microwave emitters), the average power density occurring during any period of exposure (and the resultant absorbed energy) is very low. Energy absorption in humans exposed to these systems would be considerably lower than levels suggested as safety guidelines. (Systems to be developed in the future, however, could be capable of producing higher repetition rates than are currently possible, resulting in higher average power densities.)

Jauchem and Frei (1995) investigated cardiovascular changes in unanesthetized rats exposed to high-peak-power microwaves at frequencies of 1.7–1.8 GHz (peak power density 3.3–6.5 kW/cm^2) and 1.2–1.4 GHz (peak power density 14.6–51.6 kW/cm^2). After attenuation of the sound produced by the microwave source, there was no significant change in the mean arterial blood pressure or heart rate during or after exposure.

Some electromagnetic-energy sources can produce repetitive nanosecond pulses with subnanosecond rise times and a corresponding ultrawide band of frequencies. Damage to biological tissue has been postulated to result from propagation of these pulses (Albanese et al. 1994). Adair (1995) and Merritt et al. (1995), however, performed a careful evaluation of the hypotheses of health hazards and found them to be invalid. Erwin and Hurt (1993) summarized previous studies of cardiovascular responses of anesthetized rats to ultrawideband pulses produced by a Hindenberg 2 transmitter. Animals were exposed to pulses for 2 min [60 Hz, peak electric (E)-field strength 250 kV/m, rise time 310 ps]. No difference in heart rate or blood pressure was observed after the ultrawideband exposures. Jauchem et al. (1995b) studied cardiovascular effects of exposure to a Bournlea ultrawideband pulse system (rise time 318–337 ps, maximal E field 21 kV/m, 1- or 2-kHz repetition frequency) for various periods. There was no significant change in the mean arterial blood pressure or heart rate of anesthetized rats during or after exposure.

The ultrawideband experiments mentioned above utilized special techniques, such as parallel plate transmission lines, to allow for higher energy levels to be transmitted to the animals. Levels of exposure to personnel either operating or in the vicinity of these systems would be expected to be much lower than the levels measured at the points of exposure in the animal-model experiments. [An analogous observation is that although the electric field occurring during a lightning flash may be on the order of 1 million V/m (Williams 1988), the level of exposure is greatly decreased with distance from the flash.]

The results of the aforementioned studies support the concept that cardiovascular effects are dependent on the average power density rather than the peak power density. In spite of the relatively high peak-power pulses, the extremely short duration would not appear to result in a threshold of total energy required (i.e., duration times intensity). On the basis of these findings, one would not expect significant cardiovascular effects to result from exposure to ultrawideband pulses produced by the systems mentioned above. Studies of cardiovascular changes, however, have not been reported during exposure to ultrawideband pulses produced by other exposure sources.

Concluding remarks

Aside from electric shock, which is an obvious hazard, the body of evidence suggests that other hazardous cardiovascular effects associated with EMF exposure at levels commonly encountered are unlikely. This review includes a wide variety of different types of studies and exposures. Some of the studies had obvious drawbacks and, therefore, required careful analysis in determination of the relevance to human health. Upon close evaluation, the majority of reported cardiovascular changes were found to be of questionable significance. For example, EKG changes were due to superimposed electrical potentials unrelated to any cardiac electrical phenomena. Reported changes in heart rate were possibly confounded by the experimental and statistical evaluation procedures used, were within the range of normal biological variation, or were not replicated in different laboratories.

As other investigators have mentioned (e.g., Petersen 1983), "effects" are not necessarily "hazards." The assumption that one automatically implies the other must be questioned. In considering the potential hazards of EMFs, one must raise the question: "Is this a transient physiological effect or is it a permanent effect?" (Michaelson 1982). Measurable effects may be well within the capacity of an organism to maintain a normal equilibrium or homeostasis. If, on the other hand, an individual's ability to function properly has been compromised or the recovery capability of the individual has been overcome, then the effect may be considered a "hazard."

It would not be appropriate to consider any measurable effect, even one of adaptation, to be an adverse effect. Studies showing subtle effects may not be relevant to safety standards. Members of standards-setting committees have not considered some reported effects (e.g., calcium efflux from chick-brain tissue altered by a narrow range of modulation frequencies) to be adverse or related to human health (Petersen 1991).

It appears that even if there are effects of low-level ELF EMFs or RFR on the cardiovascular system, these effects are subtle. Whether any such effect could be considered hazardous is questionable. Anderson (1993) reviewed the biological effects of ELF EMFs, including those on the cardiovascular system. He noted that "...most of the biological effects reported are quite subtle, and evidence suggests that, at least with short-term exposure, these fields impose a relatively low potential hazard to biological systems."

In terms of cardiovascular effects, epidemiology studies have not yielded any obvious cardiovascular-related hazard of long-term low-level RFR exposures. Levels of RFR that cause heating and related cardiovascular changes have been well defined and are above exposure standards.

There are a number of emerging technologies involving the use of EMFs, including new types of cellular telephones, magnetically levitated trains, and superconducting magnetic-energy storage. The possible effects of these particular EMFs on health have not been studied directly. On the basis of the current body of knowledge of EMFs in general, however, one would not expect hazards to result if the basic physical principles relating to biological effects on the cardiovascular system are similar to those applying at other frequencies.

References

Adair RK (1995) Ultrashort microwave signals: a didactic discussion. Aviat Space Environ Med 66: 792–794

Albanese R, Blaschak J, Medina R, Penn J (1994) Ultrashort electromagnetic signals: biophysical questions, safety issues and medical opportunities. Aviat Space Environ Med 65 [Suppl 5]: A116–A120

Anderson LE (1993) Biological effects of extremely low-frequency electromagnetic fields: In vivo studies. Am Ind Hyg Assoc J 54: 186–196

Anderson LE, Kaune WT (1988) Electric and magnetic fields at extremely low frequencies. WHO Reg Publ Eur Ser 25: 175–243

Barański S, Czerski P (1976) Biological effects of microwaves. Dowden, Hutchinson & Ross, Stroudsburg, Pennsylvania

Baroncelli P, Battisti S, Checcucci A, Comba P, Grandolfo M, Serio A, Vecchia P (1986) A health examination of railway high-voltage substation workers exposed to ELF electromagnetic fields. Am J Ind Med 10: 45–55

Bortkiewicz A, Zmyslony M, Palczynski C, Gadzicka E, Szmigielski S (1995) Dysregulation of autonomic control of cardiac function in workers at AM broadcasting stations (0.738–1.503 MHz). Electromagnetobiology 14: 177–191

Burr RG, Hoiberg A (1988) Health profile of US Navy pilots of electronically modified aircraft. Aviat Space Environ Med 59: 168–171

Cabanes J (1985) Medical control of employees in the electrical industry exposed to low frequency electric fields. In: Grandolfo M, Michaelson SM, Rindi A (eds) Biological effects and dosimetry of static and ELF electromagnetic fields. Plenum, New York, pp 539–556

Checcucci A (1985) An epidemiological investigation of HV substation workers: study design and preliminary results. In: Grandolfo M, Michaelson SM, Rindi A (eds) Biological effects and dosimetry of static and ELF electromagnetic fields. Plenum, New York, pp 557–569

Chiang H, Yee K-C (1979) Study of safety standards of microwave radiation. Acta Chekiang Med Coll 8: 57–62

Chokroverty S, Hening W, Wright D, Walczak T, Goldberg J, Burger R, Belsh J, Patel B, Flynn D, Shah S, Mero R (1995) Magnetic brain stimulation: safety studies. Electroencephalogr Clin Neurophysiol 97: 36–42

Clapman RM, Cain CA (1975) Absence of heart rate effects in isolated frog heart with pulse modulated microwave energy. J Microwave Power 10: 411–419

Cook MR, Graham C, Cohen HD, Gerkovich MM (1992) A replication study of human exposure to 60-Hz fields: effects on neurobehavioral measures. Bioelectromagnetics 13: 261–285

Creasey WA, Goldberg RB (1993) Safety of high speed guided ground transportation systems: potential health effects of low frequency electromagnetic fields due to maglev and other electric rail systems. Report DOT-FRA/ORD-93/31, August 1993. United States Department of Transportation, Federal Railroad Administration, Office of Research and Development, Washington, D.C.

Damji AA, Snyder RE, Ellinger DC, Witkowski FX, Allen PS (1988) RF interference suppression in a cardiac synchronization system operating in a high magnetic field NMR imaging system. Magn Reson Imaging 6: 637–640

Djordjević Z, Kolak A, Stojković M, Ranković N, Ristić P (1979) A study of the health status of radar workers. Aviat Space Environ Med 50: 396–398

Drogichina EA, Konchalovskaya NM, Glotova KV, Sadčikova NM, Snegova GV (1966) On the problems of autonomic and cardiovascular disturbances under the effects of ultrahigh frequency electromagnetic fields. ATD Report 66–124, Library of Congress, Aerospace Technology Division. Gig Tr Prof Zabol 10: 13–17

Easterly CE (1982) Cardiovascular risk from exposure to static magnetic fields. Am Ind Hyg Assoc J 43: 533–539

Erwin DE, Hurt W (1993) Biological effects of ultrawideband emissions. In: EMP Human Health Effects Science Review Panel proceedings, March 16–18, 1993. Theater Nuclear Warfare Program and Operational Medicine and Fleet Support, Bureau of Medicine and Surgery, Washington, D.C., pp 91–95

Forman SA, Holmes CK, McManamon TV, Wedding WR (1982) Psychological symptoms and intermittent hypertension following acute microwave exposure. J Occup Med 24: 932–934

Foster KR (1992) Health effects of low-level electromagnetic fields: phantom or not-so-phantom risk? Health Phys 62: 429–435

Frei MR, Jauchem JR (1989) Effects of 2.8-GHz microwaves on restrained and ketamine-anesthetized rats. Radiat Environ Biophys 28: 155–164

Frei MR, Jauchem JR (1992) Thermoregulatory responses of rats exposed to 9.3-GHz microwaves: a comparison of E and H orientation. Physiol Chem Phys Med NMR 24: 1–10

Frei M, Jauchem J, Heinmets F (1988) Physiological effects of 2.8 GHz radiofrequency radiation: a comparison of pulsed and continuous wave radiation. J Microwave Power Electromagn Energy 23: 85–93

Frei MR, Jauchem JR, Heinmets F (1989a) Thermoregulatory responses of rats exposed to 9.3-GHz radiofrequency radiation. Radiat Environ Biophys 28: 67–77

Frei MR, Jauchem JR, Padilla JM, Merritt JH (1989b) Thermoregulatory responses of rats exposed to 2.45-GHz radiofrequency radiation: a comparison of E and H orientation. Radiat Environ Biophys 28: 235–246

Frei MR, Jauchem JR, Padilla JM (1989c) Effects of field orientation during 700-MHz radiofrequency irradiation of rats. Physiol Chem Phys Med NMR 21: 65–72

Frei MR, Jauchem JR, Padilla JM (1989d) Thermal and physiological changes in rats exposed to CW and pulsed 2.8 GHz radiofrequency radiation in E and H orientations. Int J Radiat Biol 56: 1033–1044

Frei MR, Jauchem JR, Padilla JM, Price DL (1990) Field orientation effects during 5.6-GHz radiofrequency irradiation of rats. Aviat Space Environ Med 61: 1125–1129

Frei MR, Ryan KL, Berger RE, Jauchem JR (1995) Sustained 35-GHz radiofrequency irradiation induces circulatory failure. Shock 4: 289–293

Frey AH, Seifert E (1968) Pulse modulated UHF energy illumination of the heart with change in heart rate. Life Sci 7: 505–512

Gaffey CT, Tenforde TS (1981) Alterations in the rat electrocardiogram induced by stationary magnetic fields. Bioelectromagnetics 2: 357–370

Gamberale F (1990) Physiological and psychological effects of exposure to extremely low-frequency electric and magnetic fields on humans. Scand J Work Environ Health 16 [Suppl 1]: 51–54

Gamberale F, Anshelm Olson B, Eneroth P, Lindh T, Wennberg A (1989) Acute effects of ELF electromagnetic fields: a field study of linesmen working with 400 kV power lines. Br J Ind Med 46: 729–737

Gembitskiy YV (1972) Changes in the functions of the internal organs of personnel operating microwave generators. In: Petrov I (ed) Influence of microwave radiation on the organism of man and animals. NASA Technical Translation F-708. Meditsina/National Technical Information Service, Washington, D.C., p 106

Glotova KV, Sadčikova MN (1970) Development and clinical course of cardiovascular changes after chronic exposure to microwave irradiation. In: Effects of microwave irradiation. JPRS 51238. United States Joint Publication Research Service, Arlington, Virginia, pp 1–5

Gordon ZV (1966) Voprosygigieny truda i biologitcheskogo diejstvija elektromagnitnych polei sverchvysokich tchastot. (Problems of industrial hygiene and the biological effects of electromagnetic super-high-frequency fields; in Russian). Medicina, Moscow

Graham C, Cohen HD, Cook MR, Phelps J, Gerkovich MM, Fotopoulos SS (1987) A double blind evaluation of 60-Hz field effects on human performance, physiology, and subjective state. In: Anderson LE, Kelman BJ, Weigel RJ (eds) Interaction of biological systems with static and ELF electric and magnetic fields. Proceedings of the 23rd Annual Hanford Life Sciences Symposium, Batelle Pacific Northwest Laboratories, Richland, Washington, 1984; Report CONF-841041. National Technical Information Service, Springfield, Virginia, pp 471–486

Graham C, Cook MR, Cohen HD (1990) Final report: immunological and biochemical effects of 60-Hz electric and magnetic fields in humans, report DE90006671. National Technical Information Service, Springfield, Virginia

Graham C, Cook MR, Cohen HD, Gerkovich MM (1994) Dose response study of human exposure to 60 Hz electric and magnetic fields. Bioelectromagnetics 15: 447–463

Grandolfo M (1995) The standardization agreement (STANAG) on the protection of NATO personnel against radiofrequency radiation. In: Klauenberg BJ, Grandolfo M, Erwin DN (eds) Radiofrequency radiation standards: biological effects, dosimetry, epidemiology, and public health policy. Proceedings of a NATO advanced research workshop developing a new standardization agreement (STANAG) for radiofrequency radiation. Pratica di Mare, Italian Air Force Base, Pomezia (Rome), Italy, May 17–21, 1993. Plenum, New York, pp 291–294

Gurvich E, Rubtsova N, Novokhatskaya E (1995) Exposure to extremely low frequency electromagnetic fields as occupational risk factor (abstract). Epidemiology 6: S119

Hamburger S, Logue JN, Silverman PM (1983) Occupational exposure to non-ionizing radiation and an association with heart disease: an exploratory study. J Chronic Dis 36: 791–802

Hauf R (1982) Electric and magnetic fields at power frequencies with particular reference to 50 and 60 Hz. In: Suess MJ (ed) Nonionizing radiation protection. World Health Organization, Copenhagen, pp 175–197

Hauf R (1989) Biological effect of low frequency electromagnetic fields. Oesterr Z Elektrizitaetswirtsch 42: 298–300

Heynick LN (1987) Critique of the literature on bioeffects of radiofrequency radiation: a comprehensive review pertinent to Air Force operations. Report USAFSAM-TR-87-3; June 1987. USAF School of Aerospace Medicine, Brooks Air Force Base, Texas

Heynick LN, Polson P (1984) USAFSAM review and analysis of radiofrequency radiation bioeffects literature: fourth report. Report USAFSAM-TR-84-17; May 1984. USAF School of Aerospace Medicine, Brooks Air Force Base, Texas

Hocking B, Joyner K, Fleming R (1988) Health aspects of radiofrequency radiation accidents. I. Assessment of health after a radio-frequency radiation accident. J Microwave Power 23: 67–74

Hocking B, Joyner KJ, Newman HH, Aldred RJ (1994) Radiofrequency electric shock and burn. Med J Aust 161: 683–685

Hughes JT (1994) Electromagnetic fields and brain tumours: a commentary. Teratogenesis, Carcinog Mutagen 14: 213–217

Institute of Electrical and Electronic Engineers (1992) IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz. Institute of Electrical and Electronic Engineers, New York

Jauchem JR (1991) Effects of electromagnetic fields: misconceptions in the scientific literature. J Microwave Power Electromagn Energy 26: 189–195

Jauchem JR (1992) Epidemiologic studies of electric and magnetic fields and cancer: a case study of distortions by the media. J Clin Epidemiol 45: 1137–1142

Jauchem JR (1993a) Alleged health effects of electromagnetic fields and microwaves: additional misconceptions in the literature. J Microwave Power Electromagn Energy 28: 140–155

Jauchem JR (1993b) Potential confounders in epidemiologic studies of electric and magnetic fields and childhood leukemia. Environ Carcinog Ecotoxicol Rev C11: 163–183

Jauchem JR (1995a) Cardiovascular responses to radiofrequency radiation. In: Klauenberg BJ, Grandolfo M, Erwin DN (eds) Radiofrequency radiation standards: biological effects, dosimetry, epidemiology, and public health policy. Proceedings of a NATO advanced research workshop developing a new standardization agreement (STANAG) for radiofrequency radiation. Pratica di Mare, Italian Air Force Base, Pomezia (Rome), Italy, May 17–21, 1993. Plenum, New York, pp 291–294

Jauchem JR (1995b) Alleged health effects of electromagnetic fields: the misconceptions continue. J Microwave Power Electromagn Energy 30: 165–177

Jauchem JR, Frei MR (1991) Cardiovascular changes in unanesthetized and ketamine-anesthetized Sprague-Dawley rats exposed to 2.8-GHz radiofrequency radiation. Lab Anim Sci 41: 70–75

Jauchem JR, Frei MR (1992) Heart rate and blood pressure changes during radiofrequency irradiation and environmental heating. Comp Biochem Physiol [A] 101: 1–9

Jauchem JR, Frei MR (1994) Cardiorespiratory changes during microwave-induced lethal heat stress and beta-adrenergic blockade. J Appl Physiol 77: 434–440

Jauchem JR, Frei MR (1995) High-peak-power microwave pulses: effects on heart rate and blood pressure in unanesthetized rats. Aviat Space Environ Med 66: 992–997

Jauchem JR, Merritt JH (1991) The epidemiology of exposure to electromagnetic fields: an overview of the recent literature. J Clin Epidemiol 44: 895–906

Jauchem JR, Frei MR, Heinmets F (1983a) Thermal bradycardia during radiofrequency irradiation. Physiol Chem Phys Med NMR 15: 429–434

Jauchem JR, Frei MR, Heinmets F (1983b) Terminal exposure to 5.6 GHz microwaves: a comparison of continuous wave and pulsed radiation. Preprints of the Scientific Program, 54th annual meeting of the Aerospace Medical Association, Houston, Texas, May 23–26, 1983, pp 241–242

Jauchem JR, Frei MR, Heinmets F (1984a) Increased susceptibility to radiofrequency radiation due to pharmacological agents. Aviat Space Environ Med 55: 1036–1040

Jauchem JR, Frei MR, Heinmets F (1984b) Heart rate changes due to 5.6-GHz radiofrequency radiation: relation to average power density. Proc Soc Exp Biol Med 177: 383–387

Jauchem JR, Frei MR, Heinmets F (1985a) Effects of doxapram on body temperature of the rat during radiofrequency irradiation. Clin Exp Pharmacol Physiol 12: 1–8

Jauchem JR, Frei MR, Heinmets F (1985b) Effects of psychotropic drugs on thermal responses to radiofrequency radiation. Aviat Space Environ Med 56: 1183–1188

Jauchem JR, Frei MR, Heinmets F (1988) Thermal responses to 5.6-GHz radiofrequency radiation in anesthetized rats: effect of chlorpromazine. Physiol Chem Phys Med NMR 20: 135–143

Jauchem JR, Frei MR, Padilla JM (1990) Thermal and physiological responses to 1200-MHz radiofrequency radiation: differences between exposure in E and H orientation. Proc Soc Exp Biol Med 194: 358–363

Jauchem JR, Frei MR, Chang KS, Berger RE (1995a) Microwave-induced lethal heat stress: effects of phentolamine, prazosin, and metoprolol. Methods Find Exp Clin Pharmacol 17: 241–248

Jauchem JR, Frei MR, Ryan KL, Murphy MR (1995b) High-peak-power pulses from TEMPO and ultrawideband sources: heart rate and blood pressure responses in rats. Proceedings of the 17th annual scientific session of the Bioelectromagnetics Society, Boston, Massachusetts, June 18–22, 1995, pp 151–152

Jauchem JR, Chang KS, Frei MR (1996a) Alpha$_2$-adrenergic blockade increases rate of temperature rise in anesthetized rats exposed to microwaves. Proc Soc Exp Biol Med 211: 236–243

Jauchem JR, Ryan KL, Lovelace JD, Frei MR (1996b) Lethal heat stress induced by 35-GHz microwaves: effects of β_1-adrenergic blockade with esmolol. FASEB J 10: A119

Jehenson P, Duboc D, Lavergne T, Guize L, Guérin F, Degeorges M, Syrota A (1988) Change in human cardiac rhythm induced by a 2-T static magnetic field. Radiology 166: 227–230

Kanal E (1992) An overview of electromagnetic safety considerations associated with magnetic resonance imaging. Ann NY Acad Sci 649: 204–224

Kaplan IT, Metlay M, Zaret MM, Birenbaum L (1971) Absence of heart rate effects in rabbits during low-level microwave irradiation. IEEE Trans Microwave Theory Tech 19: 168–173

Kinouchi Y, Yamaguchi H, Tenforde TS (1996) Theoretical analysis of magnetic field interactions with aortic blood flow. Bioelectromagnetics 17: 21–32

Knave B (1994) Electric and magnetic fields and health outcomes – an overview. Scand J Work Environ Health 20 [Special Issue]: 78–89

Knave B, Floderus B (1988) Exposure to low-frequency electromagnetic fields – a health hazard? Scand J Work Environ Health 14 [Suppl 1]: 46–48

Knave B, Gamberale F, Bergström S, Birke E, Iregren A, Kolmodin-Hedman B, et al (1979) Long-term exposure to electric fields: a cross-sectional epidemiologic investigation of occupationally exposed workers in high-voltage substations. Scand J Work Environ Health 5: 115–125

Knepton J, De Lorge J, Griner T (1983) Effects of pulsed microwaves at 1.28 and 5.62 GHz on rhesus monkeys (*Macaca mulatta*) performing an exercise task at three levels of work. Report NAMRL-1293, March 1983. Naval Aerospace Medical Research Laboratory, Pensacola, Florida

Korpinen L, Partanen J (1994a) The influence of 50 Hz electric and magnetic fields on the extrasystoles of human heart. Rev Environ Health 10: 105–112

Korpinen L, Partanen J (1994b) Influence of 50 Hz electric and magnetic fields on the pulse rate of human heart. Bioelectromagnetics 15: 503–512

Korpinen L, Partanen J (1995) The influence of 50-Hz electric and magnetic fields on human cardiovascular autonomic function tests. Electromagnetobiology 14: 135–147

Korpinen L, Partanen J (1996) Influence of 50-Hz electric and magnetic fields on human blood pressure. Radiat Environ Biophys 35: 199–204

Korpinen L, Partanen J, Uusitalo A (1993) The influence of 50 Hz electric and magnetic fields on the human heart. Bioelectromagnetics 14: 329–340

Kristensen TS (1989) Cardiovascular diseases and the work environment. A critical review of the epidemiologic literature on nonchemical factors. Scand J Work Environ Health 15: 165–179

Lipa BJ, Sturrock PA, Rogot E (1976) Search for correlation between geomagnetic disturbances and mortality. Nature 259: 302–304

Liu LM, Rosenbaum FJ, Pickard WF (1976) Insensitivity of frog heart to pulse modulated microwave energy. J Microwave Power 11: 225–232

Malin SRC, Srivastava BJ (1979) Correlation between heart attacks and magnetic activity. Nature 277: 646–648

Manolis AS, Wang PJ, Estes NA III (1994) Radiofrequency catheter ablation for cardiac tachyarrhythmias. Ann Intern Med 121: 452–461

Maresh CM, Cook MR, Cohen HD, Graham C, Gunn WS (1988) Exercise testing in the evaluation of human responses to powerline frequency fields. Aviat Space Environ Med 59: 1139–1145

McRobbie D, Foster MA (1985) Cardiac response to pulsed magnetic fields with regard to safety in NMR imaging. Phys Med Biol 30: 695–702

Merritt JH, Kiel JL, Hurt WD (1995) Considerations for human exposure standards for fast-rise-time high-peak-power electromagnetic pulses. Aviat Space Environ Med 66: 586–589

Michaelson SM (1982) Health implications of exposure to radiofrequency/microwave energies. Br J Ind Med 39: 105–119

Miller G (1987) Exposure guidelines for magnetic fields. Am Ind Hyg Assoc J 48: 957–968

Moss CE, Booher D (1994) Assessment of nonionizing radiation exposure at a steel foundry. Appl Occup Hyg 9: 465–471

Nagano A, Yoshimura A, Asado Y, Kitamura A, Wakai Y, Akutsu T, Watanabe T, Yamaguchi M, Takubo T, Yoshino K, et al (1991) Ventilatory effects of percutaneous magnetophrenic stimulation. Front Med Biol Eng 3: 97–112

Nikolova R, Danev S, Datsov E (1995) Changes in the status of the adaptation of workers at the television relay station on top of Botev Peak. Probl Khig 20: 68–73

Obrosov AN, Skurikhina LA, Safiulina SN (1971) Effects of microwaves on the cardiovascular system of a healthy person. Vopr Kurortol Fizioter Lech Fiz Kult 28: 223–229

Orlov LL, Alekseeva NP, Galuze GI, Memetov KA, Berlin IV (1991) Pokazaniia k naznacheniiu novogo magnitoterapevticheskogo metoda pri arterial'nykh gipertenziiakh (in Russian). Sov Med 8: 23–24

Petersen RC (1983) Bioeffects of microwaves: a review of current knowledge. J Occup Med 25: 103–111

Petersen RC (1991) Radiofrequency/microwave protection guides. Health Phys 61: 59–67

Polson P, Heynick LN (1992) Analysis of the potential for radiofrequency radiation bioeffects to result from operation of the proposed ONR and Air Force high-frequency active auroral research program (HAARP) ionospheric research instrument (IRI): general analysis. Contract F33615-90-D-0606. Technical report prepared for the US Air Force Geophysics Directorate Laboratory, Hanscom Air Force Base, Massachusetts

Polson P, Heynick LN (1995) Overview of the radiofrequency radiation (RFR) bioeffects database. In: Klauenberg BJ, Grandolfo M, Erwin DN (eds) Radiofrequency radiation standards: biological effects, dosimetry, epidemiology, and public health policy. Proceedings of a NATO advanced research workshop developing a new standardization agreement (STANAG) for radiofrequency radiation. Pratica di Mare, Italian Air Force Base, Pomezia (Rome), Italy, May 17–21, 1993. Plenum, New York, pp 337–388

Presman AS, Levitina NA (1962) Nonthermal action of microwaves on cardiac rhythm. Communication I. A study of the action of continuous waves. Bull Exp Biol Med USSR 53: 36–39

Rayman RB (1995) The electromagnetic spectrum and chemical hazards. In: Ribak J, Rayman RB, Froom P (eds) Occupational health in aviation: maintenance and support personnel. Academic Press, San Diego, pp 117–165

Reilly JP (1991) Magnetic field excitation of peripheral nerves and the heart: a comparison of thresholds. Med Biol Eng Comput 29: 571–579

Resnekov L (1981) Noise, radio frequency radiation and the cardiovascular system. Circulation 63: 264A–266A

Roberts NJ, Michaelson SM (1985) Epidemiological studies of human exposures to radiofrequency radiation. Int Arch Occup Environ Health 56: 169–178

Robinette CD, Silverman C, Jablon S (1980) Effects upon health of occupational exposure to microwave radiation (radar). Am J Epidemiol 112: 39–53

Ryan KL, Frei MR, Berger RE, Jauchem JR (1996) Does nitric oxide mediate circulatory failure induced by 35-GHz microwave heating? Shock 6: 71–76

Sadčikova MN (1974) Clinical manifestations of reactions to microwave irradiation in various occupational groups. In: Czerski P, Ostrowski K, Shore ML, Silverman C, Suess MJ, Waldeskog B (eds) Biological effects and health hazards of microwave radiation. Polish Medical Publishers, Warsaw, pp 261–267

Sagan LA (1992) Epidemiological and laboratory studies of power frequency electric and magnetic fields. JAMA 268: 625–629

Saunders RD (1989) Biological effects of magnetic fields. J Radiol Protect 9: 53–54

Savitz DA, Loomis DP (1995) Magnetic field exposure in relation to leukemia and brain cancer mortality among electric utility workers. Am J Epidemiol 141: 123–134

Saznova TE (1967) Physiological effects of work in the vicinity of 400–500 kV outdoor installations. Report 46. Institute of Labor Protection of All-Union Central Council of Trade Unions, Moscow, pp 34–49

Schaefer DJ (1992) Dosimetry and effects of MR exposure to RF and switched magnetic fields. Ann NY Acad Sci 649: 225–236

Shellock FG (1995) Human thermal responses to RF-radiation induced heating during magnetic resonance imaging. Summary and results of the April 26–27, 1993, radiofrequency radiation conference, vol 2. Papers. Report 402-R-95-011. United States Environmental Protection Agency, Washington, D.C., pp 57–75

Shellock FG, Crues JV (1987) Temperature, heart rate, and blood pressure changes associated with clinical MR imaging at 1.5 T. Radiology 163: 259–262

Silny J (1981) Influence of low-frequency magnetic field on the organism. Proceedings of the 4th symposium on electromagnetic compatibility, Zurich, 10–12 March, pp 175–180

Silny J (1985) The influence thresholds of the time-varying magnetic field in the human organism. In: Bernhardt J (ed) Proceedings of the symposium on biological effects of static and ELF magnetic fields, Neuherberg, May 13–15, 1985. MMV Medizin, Munich, pp 105–112

Silverman C (1979) Epidemiologic approach to the study of microwave effects. Bull NY Acad Med 55: 1166–1181

Simmers TA, Bakker JMT de, Wittkampf FHM, Hauer RNW (1996) Effects of heating with radiofrequency power on myocardial impulse conduction: is radiofrequency ablation exclusively thermally mediated? J Cardiovasc Electrophysiol 7: 243–247

Simon NJ (1992) Biological effects of static magnetic fields: a review. International Cryogenic Materials Commission, Boulder, Colorado

Simunic D, Wach P, Renhart W, Stollberger R, Koren ZT (1995) Determination of stimulation hazard for heart cells during MRI using FEM simulation. Abstracts of the 17th annual meeting of the Bioelectromagnetics Society, Boston, Massachusetts, June 18–22, pp 54–55

Snow JS, Kalenderian D, Colasacco JA, Jadonath RL, Goldner BG, Cohen TJ (1995) Implanted devices and electromagnetic interference: case presentations and review. J Invasive Cardiol 7: 25–32

Steenland K, Beaumont J, Spaeth S, Brown D, Okun A, Jurcenko L, Ryan B, Phillips S, Roscoe R, Stayner L, et al (1990) New developments in the life table analysis system of the National Institute for Occupational Safety and Health. J Occup Med 32: 1091–1098

Stopps GJ, Janischewsky W (1979) Epidemiological study of workers maintaining HV equipment and transmission lines in Ontario. Research report. Canadian Electrical Association, Montreal

Stoupel E, Abramson E, Sulkes J, Martfel J, Stein N, Handelman M, Shimshoni M, Zadka P, Gabbay U (1995a) Relationship between suicide and myocardial infarction with regard to changing physical environmental conditions. Int J Biometeorol 38: 199–203

Stoupel E, Petrauskiene J, Kalediene R, Abranson E, Sulkes J (1995b) Clinical cosmobiology: the Lithuanian study 1990–1992. Int J Biometeorol 38: 204–208

Stoupel E, Wittenberg C, Zabludowski J, Boner G (1995c) Ambulatory blood pressure monitoring in patients with hypertension on days of high and low geomagnetic activity. J Hum Hypertens 9: 293–294

Stuchly MA (1986) Human exposure to static and time-varying magnetic fields. Health Phys 51: 215–225

Stuchly MA (1989) Exposure to electromagnetic fields in arc welding. Health Phys 56: 297–302

Subbota AG (1972) Changes in functions of various systems of the organism. In: Petrov I (ed) Influence of microwave radiation on the organism of man and animals. NASA Technical Translation F-708. Meditsina/National Technical Information Service, Washington, D.C., p 66

Sud VK, Sekhon GS (1989) Blood flow through the human arterial system in the presence of a steady magnetic field. Phys Med Biol 34: 795–805

Tenforde TS, Gaffey CT, Moyer BR, Budinger TF (1983) Cardiovascular alterations in *Macaca* monkeys exposed to stationary magnetic fields: experimental observations and theoretical analysis. Bioelectromagnetics 4: 1–9

Tikkanen J, Heinonen OP (1991) Maternal exposure to chemical and physical factors during pregnancy and cardiovascular malformations in the offspring. Teratology 43: 591–600

Tikkanen J, Heinonen OP (1992a) Risk factors for atrial septal defect. Eur J Epidemiol 8: 509–515

Tikkanen J, Heinonen OP (1992b) Occupational risk factors for congenital heart disease. Int Arch Occup Environ Health 64: 59–64

Tyasto MI, Ptitsyna NG, Kopytenko YA, Voronov PM, Kopytenko EA, Villoresi G, Yucci N (1995) Effect of electromagnetic fields of natural and anthropogenic origin on the frequency of pathology occurrence in St. Petersburg. Biofizika 40: 839–847

United States Health Care Financing Administration (1980) Commission on Professional and Hospital Activities. International Classification of Diseases, 9th rev, clinical modification, 2nd ed. DHHS publication PHS-80-1260. United States Government Printing Office, Washington, D.C.

Villoresi G, Breus TK, Iucci N, Dorman I, Rapoport SI (1994a) The influence of geophysical and social effects on the incidences of clinically important pathologies (Moscow 1979–1981). Phys Med 10: 79–91

Villoresi G, Kopytenko YA, Ptitsyna NG, Tyasto MI, Kopytenko EA, Iucci N, Voronov PM (1994b) The influence of geomagnetic storms and man-made magnetic field disturbances on the incidence of myocardial infarction in St. Petersburg (Russia). Phys Med 10: 107–117

Wagshal AB, Pires LA, Huang SKS (1995) Management of cardiac arrhythmias with radiofrequency catheter ablation. Arch Intern Med 155: 137–148

Westfall PH, Young SS (1993) Resampling-based multiple testing: examples and methods for p-value adjustment. Wiley, New York

Whittington CJ, Podd JV, Rapley BR (1996) Acute effects of 50 Hz magnetic field exposure on human visual task and cardiovascular performance. Bioelectromagnetics 17: 131–137

Williams ER (1988) The electrification of thunderstorms. Sci Am 259: 88–99

Williams RA, Webb TS (1980) Exposure to radio-frequency radiation from an aircraft radar unit. Aviat Space Environ Med 51: 1243–1244

World Health Organization (1993) Electromagnetic fields (300 Hz to 300 GHz). Environmental health criteria 137. WHO, Geneva

Yee KC, Chou CK, Guy AW (1984) Effect of microwave radiation on the beating rate of isolated frog heart. Bioelectromagnetics 5: 263–270

Yee KC, Chou CK, Guy AW (1988) Influence of microwaves on the beating of isolated rat hearts. Bioelectromagnetics 9: 175–181

Yee KC, Chou CK, Guy AW (1994) Character of the effect of microwave on conduction velocity of frog ventricular muscle. Bioelectromagnetics 15: 555–561

Zagorskaia EA, Klimovitskii VI, Mel'nichenko VP, Rodina GP, Semenov SN (1990) Effect of low-frequency electromagnetic fields on the individual functional systems of the body. Kosm Biol Aviakosmicheskaya Med 24: 3–11

Zhao Z, Zhang S, Zho H, Zhang S, Jingfen S, Lianjie L (1994) The effects of radiofrequency (< 30MHz) radiation in humans. Rev Environ Health 10: 213–215