CHAPTER 7

The Effects of Electromagnetic Energy on the Cardiovascular and Hematological Systems

Introduction

The cardiovascular system consists of the heart and the vascular tree which distributes the blood to the tissues of the body. Although the heart is somewhat independent and free running, it has neural connections that can accelerate or depress its activity. Applied EMFs could influence heart function by changing peripheral vascular resistance, by a direct action on the electrical system of the heart muscle, or by a secondary effect via the CNS.

The blood is a fluid that contains a variety of cellular elements including the red and white blood cells. Red cells carry dissolved oxygen, picked up in the lungs, to the body's other tissues; the white cells, in addition to protecting against invading microorganisms and foreign proteins, are intimately involved in local inflammation and tissue-repair processes. Both cell types are produced in the hematopoietic tissues (located primarily in the bone marrow), and they have a finite lifetime in the circulation before being replaced by new cells. The fluid portion of the blood is a mixture of many chemicals with diverse metabolic functions—chemical transport, blood clotting, and immune response are three examples.

Feedback systems that are only partially understood regulate both the cellular and non-cellular composition of blood. For example, when an organism suffers a hemorrhage or an infection, the hematopoietic tissues are mobilized to produce the required types of cells in the required numbers. As we have seen in other areas, an EMF impact on the blood could arise from a primary effect on the tissue itself, or from a secondary effect, with the field affecting the systems that regulate blood composition.

The Cardiovascular System

An electrocardiogram (ECG) is a recording of the electrical changes that accompany the cardiac cycle; a typical ECG is shown in figure 7.1.

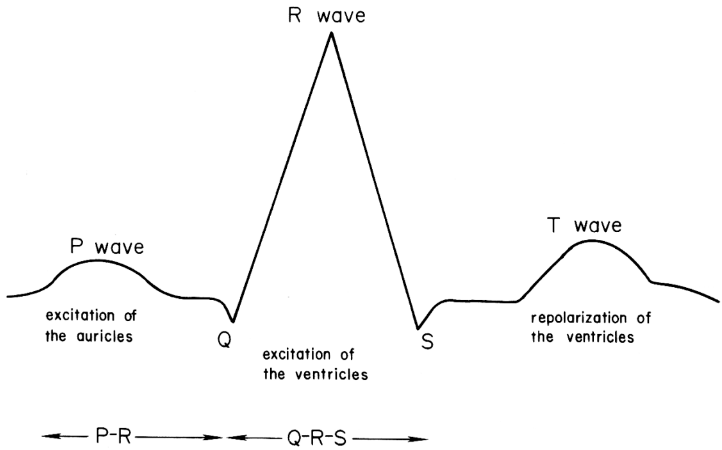

Fig. 7.1. the structure and origin of the electrocardiogram. A lengthened PR interval may indicate impairment of conduction of impulses from the atrium to the ventricle; the QRS complex is associated with interventricular conduction.

When mice were exposed for 1000 hours to 100 kv/m, 50 Hz, the PR interval and the QRS duration were each lengthened by 19.5% (1). Guinea pigs exposed acutely (30 min.) to the same field exhibited sinusal arrhythmia that began 10-20 minutes after removal from the field, and lasted 10 minutes (1).

Fischer et al. exposed rats to 50 and 5300 v/m, 50 Hz, and observed bradycardia (decreased heart rate) at both field strengths as soon as 15 minutes after commencement of exposure (2). At the lower field strength the effect was about 8%, and this decrease remained statistically signify-cant ($p < 0.01$) after 2, 10, 21, and 50 days of continuous exposure. At 5300 v/m the decrease in heart-rate after 15 minutes' exposure was about 16%: it was not seen following 2, 10, or 21 days exposure, but it was present (about a 5% decrease) after 50 days.

Bradycardia was also reported in rabbits following exposure to 50 Hz electric fields (3); at 1000 v/m, the heart-rate decreased by about 9% after 30-60 days. The field also brought about a reduction in the amplitude of the ECG: the P, R, and T waves were each reduced by 40-50%. Another effect induced by the 1000-v/m field was a reduction in the physiological reserve capacity of the rabbits. When the control animals were forced to remain in an erect position the heart-rate increased by 22-32%, but among the animals exposed to the field the range was 34-46%. No effects on heart action were seen at 500 or 100 v/m.

Microwave EMFs have produced alterations in heart function that are remarkably similar to the changes observed at 50 Hz (4). Bradycardia was observed in rabbits after 2 weeks', but not after 2 months', exposure to 0.5 and 3 v/m. The amplitudes of the P, R, and T waves in the exposed animals were decreased by about 50% following 2 weeks' and 2 months' exposure. When pituitrin was injected intravenously into control and exposed (1.5 mo.) rabbits, the resulting coronary insufficiency was stronger, and disappeared more slowly, in the exposed animals.

In preliminary studies, dogs were exposed to 15 kv/m, 60 Hz, for 5 hours to determine whether such exposure altered the physiological response to a controlled hemorrhage (10 ml/kg, over a 3-minute period) (5). The cardiovascular changes ($p < 0.05$) at the end of the hemorrhage were: mean arterial pressure fell an average of 5.9 mmHg in the control group and 16 mmHg in the exposed group; arterial pulse pressure fell 0.9 mmHg in the control group and 10.9 mmHg in the exposed group; average heart-rate decreased 9.3 beats per minute in the control group, but increased 57. 5 beats per minute in the exposed group.

Heart action is one of several factors that influence arterial blood pressure. In studies involving the exposure of rats to 153 $\mu W/cm^2$, 3 GHz, both a short-term hypertensive effect and a long-term hypotensive effect were reported (6). During the first month of the 1 hour/day exposure regimen an increased arterial pressure was seen: beginning with the second month's exposure, the arterial pressure of the exposed animals was consistently lower than that of the controls for the next 5 months. When the exposure was terminated the arterial-pressure difference disappeared within about 1 month.

Blood

Changes have been reported in the cellular composition of the blood of rats, mice, dogs, guinea pigs, and rabbits following exposure to both high and low frequency EMFs (7-15).

Graves (7) exposed mice continuously to 25 and 50 kv/m for 6 weeks and found that the white blood cell count (WBC) was increased by 20% and 66% respectively. The red blood cell count (RBC) decreased by 6% and 12% at the respective fields, but these changes were not reported to be statistically significant.

Rats exposed intermittently (30 min/day) to 100 kv/m, 50 Hz, for 8 weeks, exhibited elevated neutrophil levels and depressed lymphocyte levels (8). The same results were found following 2, 5, and 7 weeks' exposure at 5 hours/day. In dogs, alteration of the blood profile was seen following exposure at 10-25 kv/m (8).

Meda (9) found a lymphocyte decrease and a neutrophil and eosinophil increase in rats after a single 6-hour exposure to 100 kv/m, 50 Hz. A similar blood picture was found in mice after 500- and 1000-hour exposures to 100 kv/m (9). A significant increase in WBC was found in rabbits that had been exposed to 50 kv/m, 50 Hz, for 3 months (14).

As has been the case with almost all biological indicators, the time course of the changes in blood parameters following EMF exposure was not the same in each test animal (11). Guinea pigs were exposed to 3GHz, 10 min/day, for 30 days (11), and both the irradiated and the sham-exposed animals were sampled before and after each daily exposure bout. The sham-exposed group revealed no significant changes, but animals exposed to 25 or 50 μW/cm2 exhibited EMF-induced alterations with time dependencies that differed with each animal. For a given exposure duration, the WBC was above the normal level in some animals, and below it in others; as a result, the average values varied little during the study. At 500 $\mu W/cm^2$, however, even on the average there was a pronounced leukopenia and lymphocytosis.

Gonshar exposed rats to 2.4 GHz, 7 hours/day for 30 days and studied the effect on the levels of alkaline phosphatase and glycogen (two indicators of cellular activity) in the neutrophils (12). Glycogen increased following 3 days' exposure at both 10 and 50 $\mu W/cm^2$; after 7 days' exposure it decreased to the control level. In contrast to this apparent adaptational response, there was a sustained depressing effect on glycogen content at 500 $\mu W/cm^2$ which was still observed after 30 days' exposure. At all three intensities, the alkaline phosphatase levels first increased then decreased below the control level within 30 days.

Ferrokinetic studies demonstrated that iron metabolism was affected and that erythrocyte production (measured by 59Fe incorporation) was significantly decreased in rabbits exposed to 2.95 GHz, 3000$\mu W/cm^2$, for 2 hours daily (15). The effects seen after 37 days of irradiation with a pulsed EMF were comparable in magnitude to those seen after 79 days exposure to a continuous-wave EMF.

Rats exposed to 130 gauss, 50 Hz, for 4 hours/day, exhibited a 15% reduction in RBC after 1 month's exposure: the RBC level returned to normal within a month after removal of the field (10).

Because comparable results were obtained using widely different EMFs, the blood-composition studies suggested to us that the EMF-induced alterations were mostly transient compensatory reactions of the body to a change in the electromagnetic environment. To determine the relation between magnitude and direction of the response and the conditions of application of the external EMF, we looked for changes in hematological parameters of mice due to short-term exposure to a full-body vertical 60 Hz electric field of 5 kv/m (13). To ensure maximum statistical sensitivity every mouse was sampled twice, once after exposure to the field for 2 days and once following a 2-day nonexposure period. There were four consecutive experiments, two with males and two with females. In each there were two groups: one for which the control period preceded the exposure period (nF→F), and one in which the pattern was reversed (F→nF). On "day 1" of each experiment the mice were divided into the two groups and the electric field was applied to one-half the population. On "day 3" the blood parameters were measured in each mouse and immediately thereafter the exposed and nonexposed groups were interchanged. On "day 5" the blood parameters were measured again and the mice were killed.

Blood was collected from the ophthalmic vessels and it was therefore necessary, before applying the field, to determine the influence of the first blood collection procedure on the values measured after the second such procedure. We measured the blood parameters in two groups of mice, one male and one female, under conditions that were identical in all respects to those employed during the field-exposure portion of the study, and we found that the method of blood collection had a tendency to produce higher RBC, Hct, and MCV values and lower values of Hb, MCH, and MCHC (Table 7.1).

Table 7.1. Percent Change in Hematological Parameters

Experiment	Condition	Percentage Change					
		RBC	Hct	Hb	MCV	MCH	MCHC
A							
Male Control	nF→nF	1.7	2.0	-4.5*	1.0	-6.2*	-6.3*
Female Control	nF→nF	3.9*	4.1*	1.7	0.2	-5.0*	-5.1*
B							
Male I	F→nF	-4.7*	-5.1*	NM	0	NM	NM
	nF→F	-5.2*	-4.9	NM	0.2	NM	NM
Male II	F→nF	-9.0*	-9.1*	-3.3*	-0.4	5.7*	6.0*
	nF→F	-6.5*	-7.0*	-2.4*	-0.7	3.9*	6.1*
Female I	F→nF	-4.1*	-4.6*	-4.2*	-1.2	0.5	1.2
	nF→F	-6.4*	-6.7*	-3.4*	-0.5	3.8	4.8
Female II	F→nF	-5.3*	-6.0*	3.4	-1.2*	8.3*	10.0*
	nF→F	-7.1*	-9.2*	3.5	-2.3*	11.0*	13.6*

NOTE: RBC, red blood cell concentration; Hct, hematocrit; Hb, hemoglobin; MCV, mean cell volume; MCH, mean corpuscular hemoglobin; MCHC, mean corpuscular hemoglobin concentration. *A*, no change in exposure conditions; *B*, change in exposure condition as indicated. NM, not measured.

$p < 0.05$

The results obtained in connection with the application of the electric field are shown in table 7.1. In each experiment, RBC on "day 5" was significantly less than on "day 3," regardless of whether the interval between "day 3" and "day 5" was an exposure period or a nonexposure period. A decline in Hct paralleled the RBC changes, but Hb showed no consistent changes. MCV showed a tendency to decrease, but the other computed indices both increased, since the cell loss overshadowed any decrease in hemoglobin concentration.

The trends in the computed indices, and especially the changes in RBC and Hct, were opposite to those induced by our method of blood collection alone. It follows, therefore, that the applied electric field had a physiological impact. The unique feature of the observed responses is that, for each parameter, a change in the same direction occurred with both the F→nF and nF→F groups. An analysis of variance confirmed that in all four experiments there was an effect associated with time but not with the order of field application. This indicated that the animals responded to the change in their electrical environment, not to the electric field itself.

There are two reports of the effects of EMF on the blood globulin (16, 17). When rats were exposed to 3000 v/m at 1 KHz for 8 and 20 days (20 min./day), a reduction in coagulation activity (expressed as a lengthening of the rethrombin time, a drop in plasma tolerance for heparin, and a decrease in prothrombin consumption), and a rise in the thromboplastic and fibrinolytic activity of the blood were found (16). We found that rats exposed to DC electric fields of 2.8-19.7 kv/m had altered blood-protein distributions (17). The general trend was towards elevated albumin and decreased gamma globulin levels (expressed as a percent of the total blood proteins).

Immune Response

An immune response is triggered by the invasion of a physical agent and it is characterized by the appearance of circulating antibodies (humoral immunity), and the emergence of immunologically committed cells (cellular immunity). Recognition of the intruding agent is accomplished by the antibodies (produced by lymphocytes), and the subsequent phagocytic activity is carried out by neutrophils, monocytes, and macrophages. Thus, both humoral and cellular mechanisms are intimately meshed in the functioning of the immune-response system.

One of the fundamental roles of the immune system is to protect the host from bacterial infection. Both high- and low-frequency EMFs have been shown capable of impairing resistance to infection (18, 19). Szmigielski et al. (18) studied the action of an EMF on the granulopoietic reaction in rabbits that had been subjected to an acute staphylococcal infection. Rabbits were exposed to 3000 μW/cm^2, 3 GHz, 6 hours/day, for 6 or 12 weeks, and then were infected intravenously with *S. aureus Wacherts*. Four to six days after infection the 6-weeks exposed animals displayed stronger granulocytosis than did the control animals, but this was reversed by the end of the observation period (Fig. 7.2A). These changes were

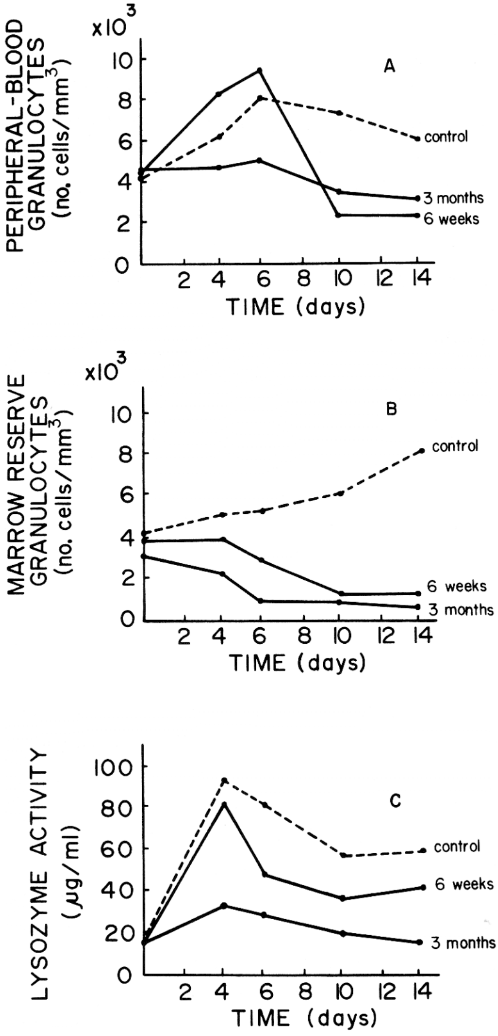

Fig. 7.2. Granulopoietic reaction in infected rabbits exposed to an EMF.

accompanied by a consistent reduction in the bone-marrow reserve pool (Fig. 7.2B), and a depressed lysozyme activity (Fig. 7.2C). Animals exposed for 3 months displayed consistently depressed granulocytosis after the staph infection (Fig. 7.2A), and both the bone-marrow reserve pool and the blood serum lysozyme activity were lowered during the entire postinfection period (Fig. 7.2B and C). The results were interpreted to mean that the EMF-exposed animals lacked the reserve capacity to adapt to the infection as efficiently as the control animals: fewer granulocytes could be mobilized, and there was a resulting decline in lysozyme activity. In related *in vitro* studies, rabbit granulocytes were exposed to 1000-5000 $\mu W/cm^2$ for 15-60 minutes to assess the effect on the cell membrane (20). An increase in the number of dead cells and a rise in the liberation of lysosomal enzymes were found.

A 200 gauss, 50 Hz EMF also altered the natural resistance to infection (19). Following EMF exposure, mice were injected intraperitoneally with various concentrations of Listeria. The initial cell concentration required to kill half the animals was about one-fifth of that which produced the same killing effect in the controls. Additionally, the exposed animals exhibited more extensive bacterial growth in the lymph nodes, liver, and spleen, and the phagocytic activity of their blood cells was decreased.

There are several reports of altered phagocytic capability in animals exposed to high-frequency EMFs (21-24). When rats were exposed intermittently over a 6-month period to a pulsed EMF it was reported that neutrophil phagocytic activity and blood-plasma bacteriocidal activity (determined using agar cultures of E. coli) were both decreased (21). Similar results were seen following the exposure of rats to 100 and 2250 v/m, at 14.88 MHz (22): at both field strengths, there was a marked increase in phagocytic activity of the neutrophils during the first month's exposure followed by a prolonged period of inhibited activity which lasted until the end of the 10-month exposure period.

Shandala and Vinogradov also studied the effect of an EMF (1-500 $\mu W/cm^2$, 2.4 GHz, for 30 days) on the phagocytic action of neutrophils in peripheral blood (23). Using guinea pigs, they found that the percent of killed microbes increased following exposure to 1-10 $\mu W/cm^2$; and decreased at 50 and 500 $\mu W/cm^2$; the most pronounced effects occurred at 1 $\mu W/cm^2$. EMF-induced alterations in the complement titer in blood serum were also found. Both immunological indicators returned to normal within two months of the cessation of irradiation. A similar inhibition of antibody production was found in rabbits following exposure at 50 $\mu W/cm^2$ (25).

In later studies, Shandala et al. reported a significant disturbance in the immunological system of rats exposed intermittently to 500 $\mu W/cm^2$ for 30 days (26): blast cells in peripheral blood, and the rosette-forming cells in the spleen and thymus were both altered following EMF exposure.

EMFs have been reported to alter the response of immunocompetent lymphocytes (27, 28). Mice, exposed intermittently to 500 $\mu W/cm^2$, 2.95 GHz for 6 and 12 weeks, were challenged with an injection of sheep red blood cells and the immune response was characterized by the number of lymphocytes and plasmocytes in the lymph nodes. In the 6-weeks exposed animals, the time course of the antibody-forming cells population was significantly different from that of the controls; the maximum difference occurred 6-8 days after injection of the antigen, and the effect was no longer observed after 20 days (27). Exposure for 12 weeks prior to injection resulted in no difference in immune response as compared to the controls, indicating that the mice had become adapted to the field.

The immunological reaction of guinea pigs exposed to an atmosphere of formaldehyde or carbon monoxide was altered when the animals were pretreated for 1 month with an EMF (5-50 $\mu W/cm^2$, 2.4 GHz, 7 hr./day, for 1 mo.) (28).

B-lymphocytes (responsible for humoral antibody synthesis) and neutrophils are each derived from bone-marrow stem cells. Czerski et al. reported that guinea pigs subjected to a pulsed EMF (2.9 GHz, 1000 $\mu W/cm^2$, 4 hr./day for 14 days) exhibited an abnormal circadian rhythm of bone-marrow stem-cell mitoses (30). In a comparable study involving guinea pigs, it was found that the EMF altered megakaryocytic activity in the bone marrow (29); it stimulated increased levels of megakaryocyte destruction, and a compensatory proliferation of megakaryoblasts.

Inflammation is a local response of vascular tissue to irritation or injury; it involves the passage of fluid containing WBCs and proteins from the blood into the tissues. This nonspecific protective response was found to be susceptible to an EMF (31). An aseptic inflammation in the peritoneal cavity of mice was induced by the implantation of a glass slip; in the resulting foreign-body reaction the glass became covered with a cell monolayer, but this response was delayed in mice that had been exposed to DC magnetic field of 600-3800 gauss.

Since 1976, investigators at Battelle Laboratories have consistently failed to observe 60-Hz biological effects in many areas including the cardiovascular, hematological and immune-response systems (32); these studies are analyzed elsewhere (33).

Summary

The effects of EMFs on the cardiovascular system include bradycardia, decreased physiological reserve capacity, and alterations in blood pres sure. Heart action may be particularly sensitive to EMF: a decrease in heart-rate was seen after 15 minutes exposure to 50 v/m, 60 Hz (z). The changes in the low-frequency studies were strikingly similar to those reported in humans who were occupationally exposed to power-frequency fields (see chapter 10).

Several studies have reported impacts of EMFs on cellular and noncellular components of blood. As we have seen previously, similar kinds of changes occurred following exposure to widely different EMFs (10, 15), and the direction of the changes differed with each animal. (11). The EMF effects on RBC and WBC were time dependent; in the case of RBC, there is evidence to indicate that animals can respond to a change in electromagnetic environment (13) as well as to the magnitude of the EMF. This is a good agreement with results described earlier showing that intermittent exposure produced different, usually greater, reactions than did continuous exposure to the same EMF.

An organism whose physiological reserve capital is being expended in a process of adaptation to an environmental agent would be expected to exhibit a reduced capacity to deal with a second simultaneous agent. This is exactly what has been seen in the immune-response studies: the fields impaired resistance to infection, decreased phagocytic activity, and altered both cellular and humoral immunocompetence.

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