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BIOLOGICAL EFFECTS OF EXTREMELY LOW FREQUENCY ELECTROMAGNETIC FIELDS

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Power Frequency Electric Fields and Biological Stress: A Cause-and-Effect Relationship

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ABSTRACT

We previously advanced the hypothesis that electric power frequency fields are biological stressors. It is a well-established physiological principle that an anima undergoing a stress will exhibit a diminished capacity to cope with a second simultaneous stress. To test the specific hypothesis, therefore, that a 60-Hz electric field of 5000 V/m can be a biological stressor, we performed fibular fractures on a number of rats; one-half the group was exposed to the field and half was maintained as a control. The rats were housed individually in totally plastic enclosures. Both food and water were supplied on essentially the same equipotential plane as that occupied by the animals. The fractures were performed at the midshaft, and the extent of healing was assayed 14 days thereafter on the basis of blind scoring of serial histological preparations. At 14 days after fracture, the degree of healing manifested by the exposed animals was substantially less than that of the unexposed animals. The entire experiment was repeated; there were identical results. When rats were exposed at 1000 V/m in two replicate experiments, however, no differences were seen in the degree of fracture healing. We conclude that a 60-Hz electric field of 5000 V/m has been shown to be a biological stressor in the mammalian system we used.

As late as 1974 there was no substantial interest in the biological consequences of high-voltage transmission lines. Today there is concern in many quarters because such lines present some significant environmental problems. The task of assessing the risk from exposure to the electric and magnetic fields of high-voltage lines is a notable example. Since biologically significant subthreshold currents can occur many feet from high-voltage lines whenever a subject contacts

a grounded metal object (Spadaro, 1977; Deno and Zaffanella, 1975), the biological consequences of grounding microcurrents must also be determined. Beyond fields and currents problems associated with synergistic interactions and magnetospheric stimulation are presented. Transmission-line energy fluxes, for example, consist of essentially simultaneous spatial electric and magnetic fields (Hart and Marino, 1977). The effect of a comparable environment on test animals must therefore be determined. Basic public health considerations also require consideration of the possibility of synergistic interactions between the transmission-line flux and other environmental electromagnetic fields (Becker, 1977). Perhaps the most surprising and unexpected impact of high-voltage lines is their ability to alter events in the earth's magnetosphere (Park and Helliwell, 1978), the significance of which is at present undetermined.

Many different investigational pathways have come together in one transmission-line problem area, i.e., the biological effects of electric and magnetic fields (Marino and Becker, 1977). A series of German studies have shown that test organisms are sensitive to the ambient electromagnetic field and that weak low-frequency electric fields are effective surrogates for the more-complex atmospheric fields (Wever, 1974; Altman and Soltau, 1974; Lang, 1972). A series of studies on monkeys and human beings at the Naval Aerospace Medical Research Institute established the biological activity of low-frequency magnetic fields (Beischer, Grissett, and Mitchell, 1973; Gibson and Moroney, 1974; Grissett et al., 1977). Studies for the American Electric Power Company and the Electric Power Research Institute found, or appeared to find, biological effects due to low-frequency field exposure in mice, dogs, and chickens (Knickerbocker, Kouwenhoven, and Barnes, 1967; Gann, 1976; Bankoske, McKee, and Graves, 1976). Beginning around 1970 a flood tide of Soviet reports appeared in which low-frequency fields were reported to produce numerous adverse biological changes (Novitskiy et al., 1971; Lyskov, Emma, and Stolyarov, 1975; Dumanskiy, Akimenko, and Prokhvatilo, 1977). A line of studies by American ornithologists revealed that low-frequency fields can disrupt bird orientation (Southern, 1975; Williams, 1976; Larkin and Sutherland, 1977). Behavioral effects in humans and monkeys after even acute exposure to low-frequency fields have been reported by many investigators (Hamer, 1968; Friedman, Becker, and Bachman, 1967; Persinger, Lafreniere, and Mainprise, 1975). The most common effects found after exposure to low-frequency fields are attributable to field-induced stress. These include changes in the classic parameters of the general-adaptation syndrome and changes arising from the general debilitating effects of field-induced stress

(Blanchi et al., 1973; Marino, Becker, and Ullrich, 1976; Noval et al., 1976; Hauf, 1976; Popovich and Koziarin, 1977; Mathewson et al., 1977). Finally, on the clinical side low-frequency fields have produced changes in bone physiology (Bassett, Pawluk, and Pilla, 1974; Watson, DeHaas, and Hauser, 1975; Norton, Rodan, and Bourret, 1977).

The challenge presented in the short run calls for the elaboration of experiments that will permit specific assessment of the risks to the public of exposure to the fields of high-voltage lines. In the long run more specialized studies will be required to sort out many details of the field effects. We have addressed ourselves primarily to the problem of obtaining data from test animals exposed under realistic conditions, i.e., those admitting of a reasonable parallel with exposure of the public to high-voltage lines.

In our view the evidence shows that, in addition to whatever specific effects which they may cause, low-frequency fields can be biological stressors. Stress has a recognized clinical relationship to healing; namely, factors that induce a stress response thereby retard healing. To test the hypothesis that electric fields can be biological stressors, we studied the effects of 60-Hz electric fields on the extent of fracture healing in rats.

METHODS

Our procedure consisted essentially of the histological evaluation of the impact of a full-body electric field on the degree of fracture healing.

Male Sprague-Dawley rats, 21 days old, were obtained commercially and acclimatized to our animal care facility for 6 days prior to study. Subsequently a fracture was surgically induced in one fibula of each animal (Fig. 1). With the animal under anesthesia, a small incision was made on the lateral margin of the leg midway between the fibular head and the lateral malleolus. With the skin retracted the fascial plane between the posterior-compartment plantar flexor muscles and the lateral-compartment peroneal muscles is bisected. Gently separating the two muscle groups exposes the shaft of the fibula, and a midshaft fracture was produced with sharp, fine-tipped scissors. The fracture was summarily reduced and the wound closed with 4-0 silk sutures. The rats were then divided into control and experimental groups, with an equal number of fractures of the right and left fibula contained in each. Because the fibula in the rat is connected at both the top and the bottom to the major weight-bearing leg bone—the tibia—external means of fracture

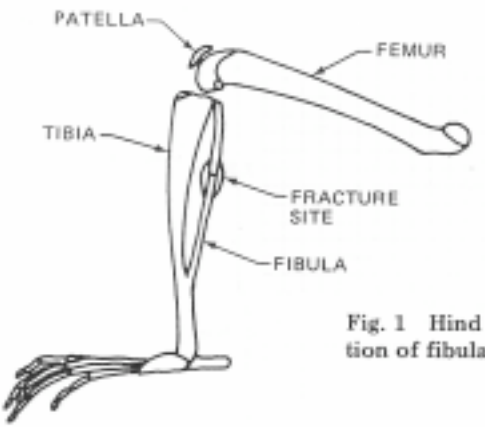

Fig. 1 Hind limb of rat with location of fibular fracture.

stabilization were unnecessary. Exposure was commenced immediately after fracture.

The electric field exposure system was a result of more than four years of development. Our basic approach was to adhere to accepted practices for housing and caring for laboratory rats, subject to the minor modifications required by the nature of the experiment. The animals were housed individually in standard nonmetallic cages contained in specially constructed exposure assemblies (Figs. 2 and 3). Each shelf consisted of a metal plate sandwiched between two layers of wood. The assemblies, housing, respectively, the control and experimental rats, consisted of three pairs of vertically arranged shelves. In the assembly housing the control rats, the plates were electrically grounded. In the second assembly the lower plates were connected to a voltage source and the upper plates were grounded, and an electric field of the desired strength in three regions was thereby created. Each cage was supported by 1-in.-thick closed-cell foam rubber to negate the possibility of artifacts' arising from field-induced vibration. With this technique, we had found previously that any interference from vibration can be eliminated, even at much stronger fields than those used in these studies (Marino et al., 1977). All animals were housed throughout the study in the same windowless room, in which the 12-hr light-12-hr dark cycle commenced at 6 a.m., the temperature was 72 ± 2°F, and the humidity, which was not directly controlled, was generally less than 50%. To ensure that there was a readily reproducible environment surrounding the control animals, we encircled the volume between the plates of the control assembly completely with grounded aluminum screening, thereby creating essentially a Faraday cage. To control for the consequently reduced light levels between the plates,

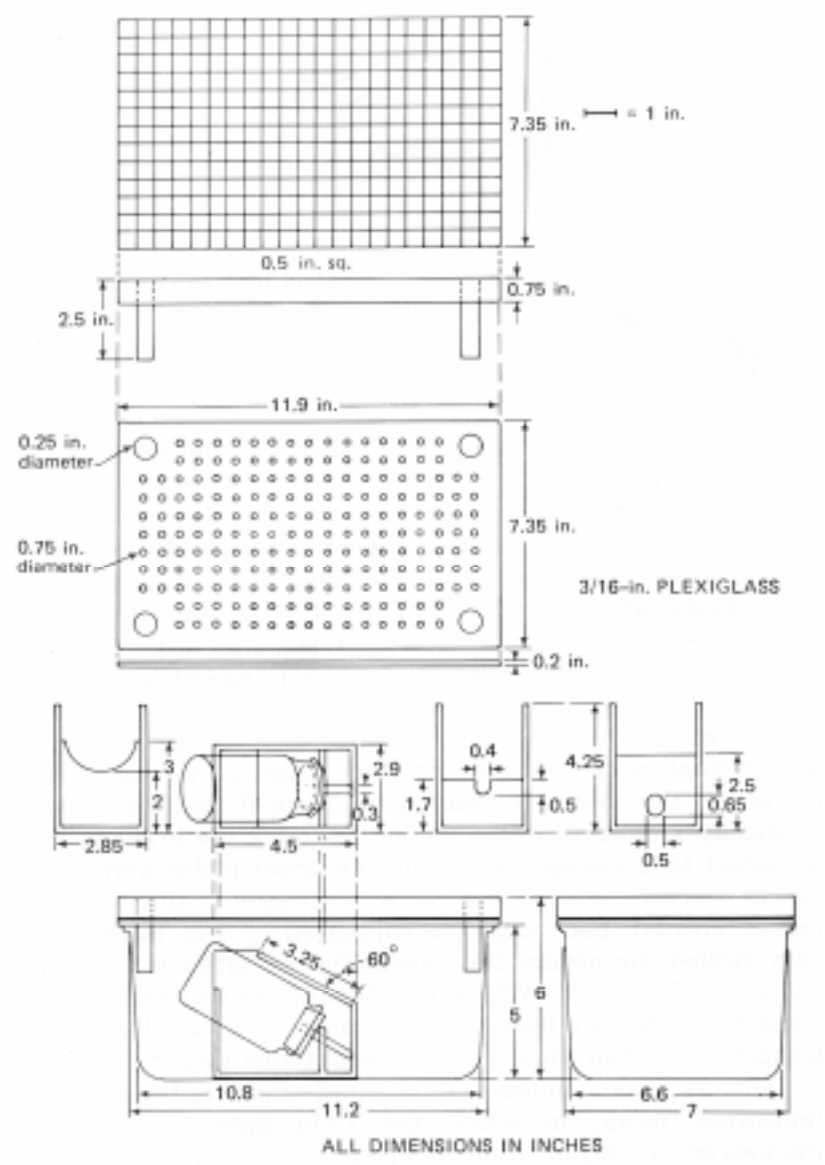

Fig. 2 Cage and water bottle holder.

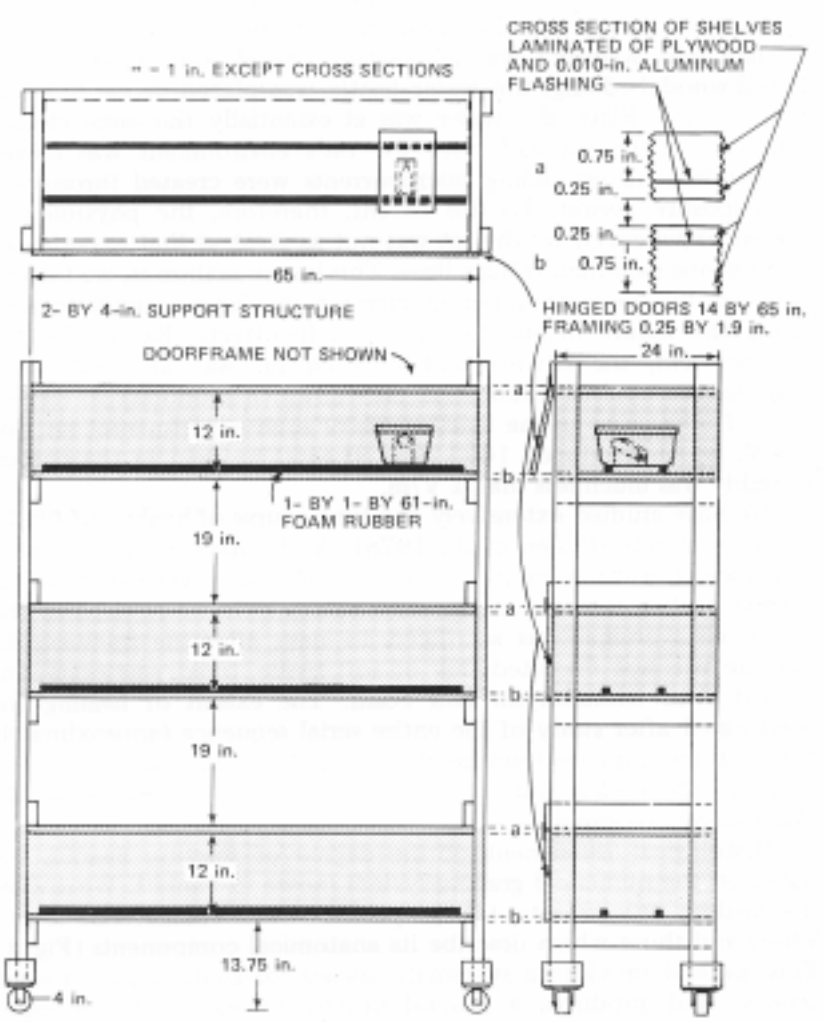

Fig. 3 Exposure assembly.

we similarly encircled the volume between the plates of the experimental assembly with fiberglass screening that had light-transmitting properties identical with those of the aluminum. Feeding and watering was ad libitum. Food was placed on the shaved-wood bedding; the water bottle was placed inside the cage with the rat. Since the water was at essentially the same electric potential as the rat and since the rat's environment was totally nonmetallic, no grounding microcurrents were created throughout the exposure period. To this extent, therefore, the physiological burden experienced by the rat was not as great as that experienced by someone near high-voltage lines. This loss in realism is, we believe, balanced by the corresponding increase in clarity gained thereby about the nature of the field-induced bioeffects. Except for the electric field, the environment of each rat was identical in all respects. We applied 1590 V, at 60 Hz, which produced an electric field of 5000 V/m in the living space of each experimental rat, and 320 V, which produced 1000 V/m. The 60-Hz field in the control assembly was much less than 1 V/m.

We have studied extensively the time course of healing of fibular fractures in rats (Cullen et al., 1978). At 14 days after fracture, a multifaceted histological picture is presented and deviations from the normal healing rate are most easily seen and documented. For this reason each animal was sacrificed 14 days after the fracture; the fracture site was dissected free of soft tissue, fixed, sectioned, and stained with hematoxylin and eosin. The extent of healing was determined after study of the entire serial sequence (approximately 150 sections) for each fracture. So that subliminal prejudice could be avoided, the coded slides were graded without reference to the experimental treatment.

Histological assessment of the degree of fracture healing was based on the numerical grading system shown in Table 1. We divided the healing process into the properties which characterize it as a whole and those which describe its anatomical components (Fig. 4). This method provides a systematic means for analyzing the healing process and produces a general healing profile in which union represents the most general description of the fracture repair process. The regional categories relate cartilage and bone to particular areas of the callus; they are the most sensitive and specific measures of fracture healing. The summing over of all five categories yielded the healing index, a high value of which indicates advanced fracture repair. For each parameter the means of the experimental and the control groups were compared by a two-tailed *t* test. Also, the group variabilities were compared by computing the variance ratio $F = (s_1/s_2)^2$, where s_1 and s_2, respectively, were the larger and

TABLE 1
Fracture-Healing Grading System

	Histological evaluation	Numerical value
	General Characterization	
Union	Fibrous clot	1
	Fibrous connective tissue and cartilage	2
	Cartilage only	3
	Cartilage and cancellous bone	4
	Cancellous bone	5
	Compact bone	6
	Remodeled compact bone	7
Alignment	Poor	0
	Fair	1
	Good	2
Callus size	Minimal	1
	Average	2
	Extensive	3
	Attenuated by remodeling	4
	Regional Characterization	
Cartilage		
	None	0
In the anchoring callus	Healthy, small amount	1
In the bridging callus	Healthy, large amount	2
In the uniting callus	Hypertrophic, small amount	3
In the sealing callus	Hypertrophic, large amount	4
	Extensive resorption	5
Bone		
	None	0
In the anchoring callus	Thin trabeculae-cartilage cores	1
In the bridging callus	Thin trabeculae without cartilage	2
In the uniting callus	Thick lamellar trabeculae	3
In the sealing callus	Compact bone	4
	Remodeled compact bone	5

smaller percent standard deviations of the groups that contained n_1 and n_2 observations. The usual tables for F with (n_1 - 1, n_2 - 1) degrees of freedom were used to determine if s_1 was significantly different from S2 (Snedecor and Cochran, 1967).

The experiments at both field strengths were repeated, and the results were found to be identical. Consequently no distinctions are made between the replicates. Every animal placed on study survived until sacrifice.

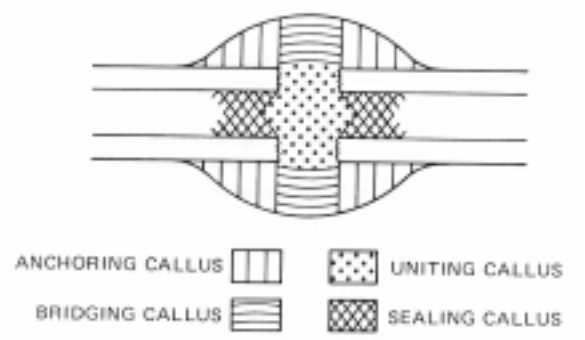

Fig. 4 Regional distinctions in fracture callus.

RESULTS

The fractures in rats exposed to 5000 V/m exhibited a distinctly altered histological appearance compared with those of the control rats. The healing callus in the control group was dominated by new trabecular bone several lamellae thick. New periosteal compact bone was also found in the region of anchoring callus. Cartilage, if present, was limited to isolated regions of the bridging and uniting callus and was sometimes observed in the central portion of the more delicate trabeculae. The cartilage was generally hypertrophic, i.e., chondrocytes were swollen and had nuclei with varying degrees of pyknotic condensation. Often chondroclasts were seen in necrotic areas of cartilage. Some fractures displayed such an advanced degree of healing that the fracture site was not readily apparent. In these cases the necrotic fragment ends provided the only landmarks for identifying the region of the fracture because new compact bone completely filled the fracture gap and no external callus was present. In the field-exposed animals, the new bone had much thinner trabeculae—most with cartilaginous cores-than in the control animals. Large blocks of cartilage were evident throughout the callus. In some instances a cartilage plate was seen at the union site in the region of the uniting callus. This cartilage exhibited typical epiphyseal plate organization with zones of resting, proliferating, hypertrophic, and calcifying cartilage, often at both the superior and inferior margins. New compact bone was strictly limited to the anchoring callus and was never extensively developed. After 2 weeks of field exposure, fractures exhibited less new bone formation, and correspondingly more cartilage, than did the control fractures. Characteristic fracture sites in control and experimental rats are shown in Figs. 5 and 6.

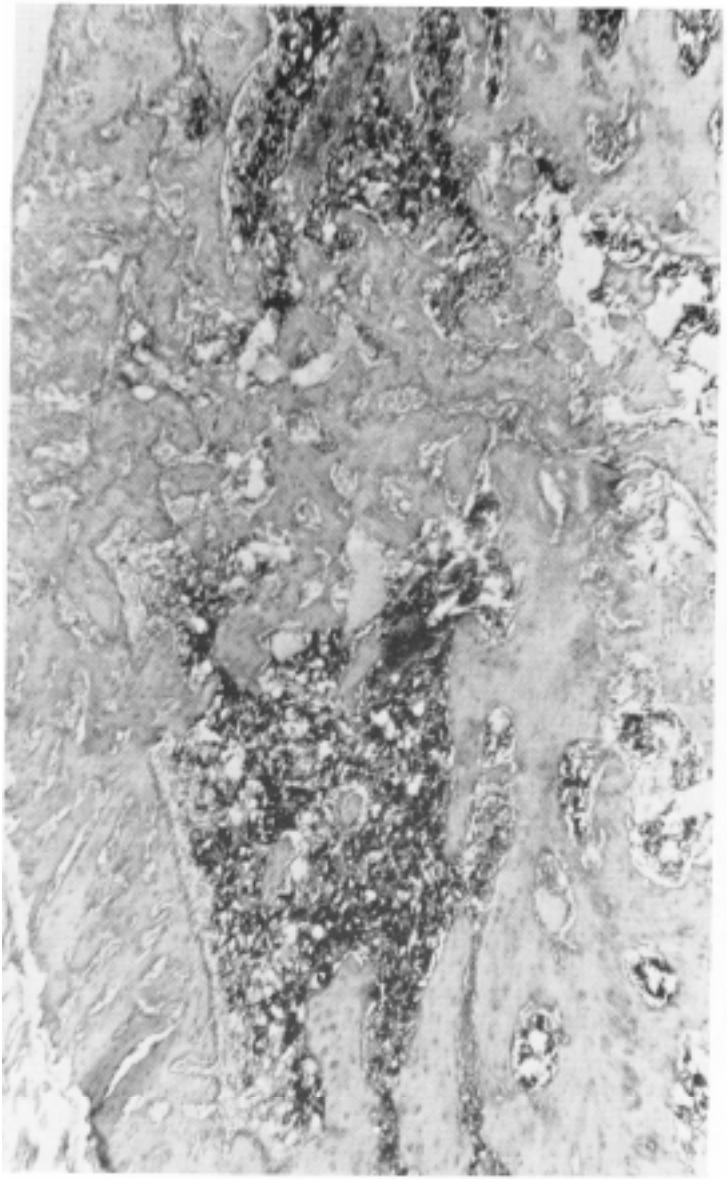

Fig. 5(a) Fracture site in control rat at 14 days after fracture. Darkened areas to the left and right are marrow cavities of the broken-bone fragments. Union by new bone is complete. (Magnification, 40 ×.)

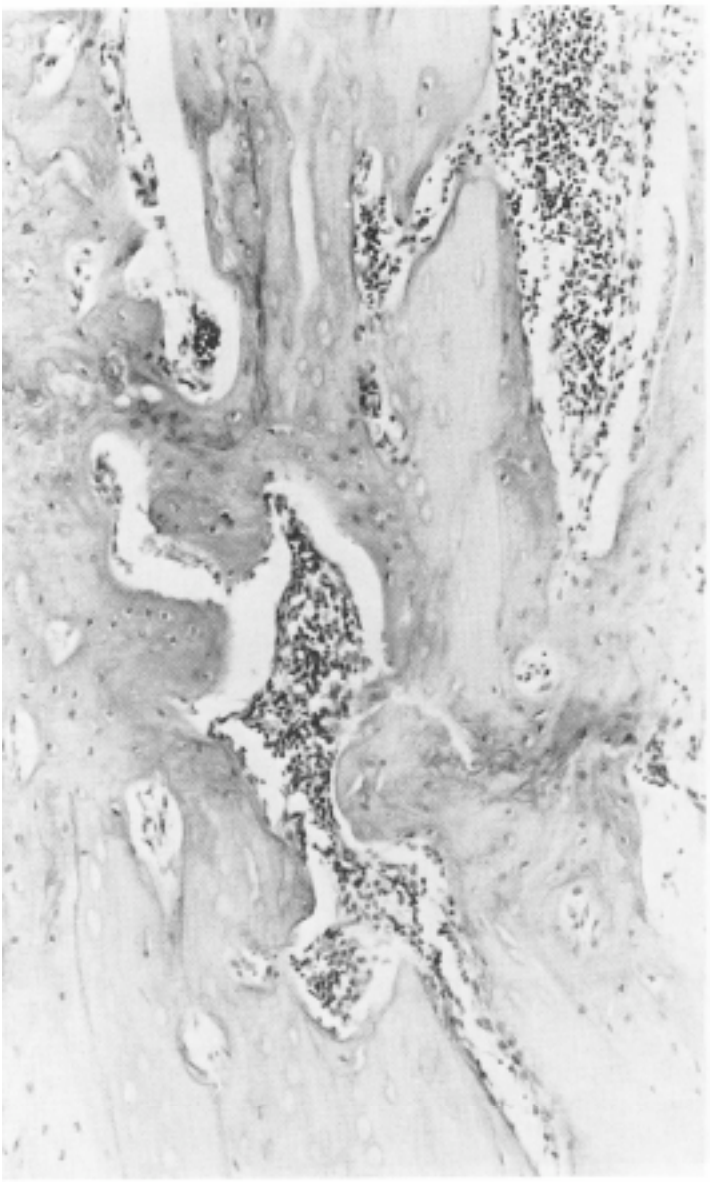

Fig. 5(b) Fracture site in control rat at 14 days after fracture. Dead-bone fragments are marked by regions of empty cavities that formerly contained bone cells. Bone ends are linked together by new bone growth several lamellae thick. (Magnification, 100 ×.)

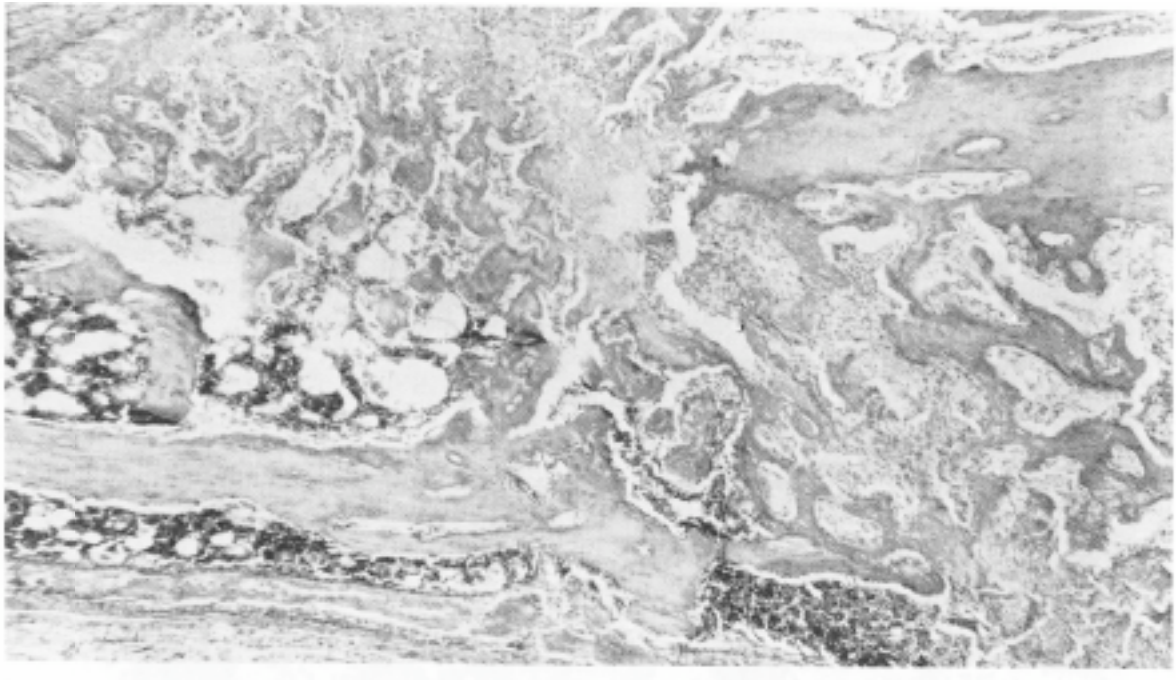

Fig. 6(a) Fracture site in rat exposed to 5000 V/m at 14 days after fracture. Most of the fracture callus can be seen. Necrotic fragments project into the center of the field. Bony union is incomplete owing to the presence of a large cartilaginous mass above the left bone fragment. Remaining areas are composed of trabecular bone and fibrous connective tissue. (Magnification, 40 X.)

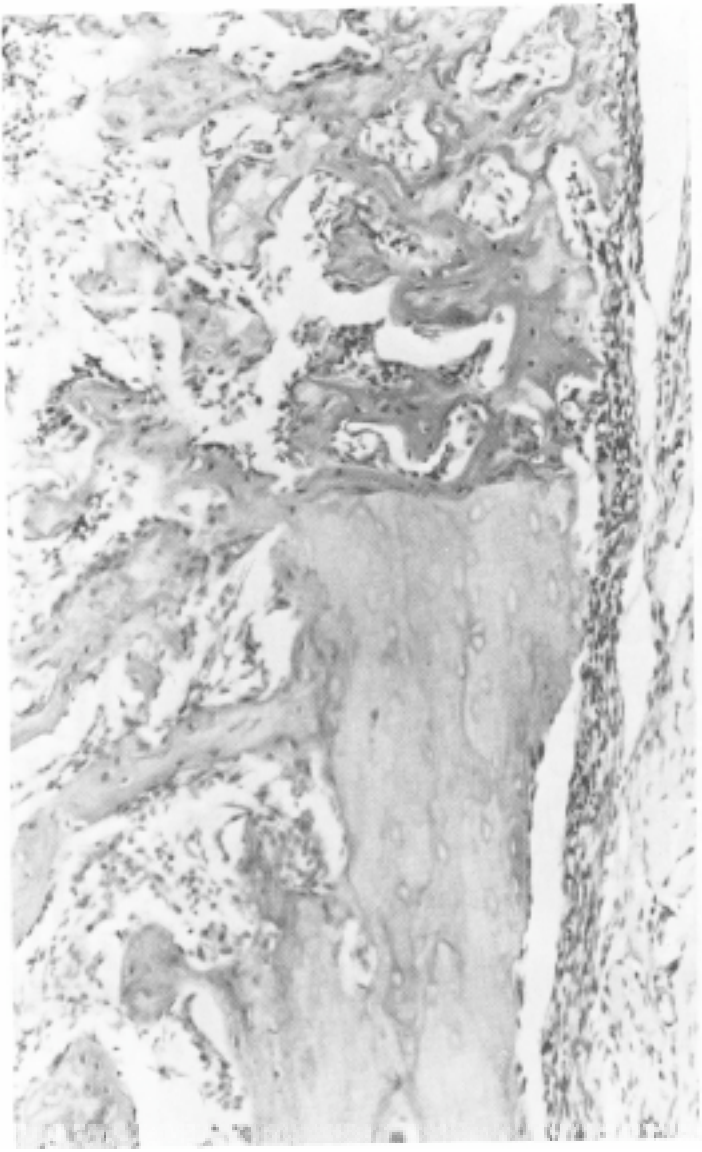

Fig. 6(b) Fracture site in rat exposed to 5000 V/m at 14 days after fracture. Necrotic fragment at left is joined by new bone growth. Trabeculae are immature and very thin. Lighter areas in the trabeculae are residual cartilage. (Magnification, 100 ×.)

The rats exposed at 1000 V/m did not exhibit retardation in fracture healing. The experimental as well as the control fractures presented a healing callus composed primarily of new bone. In both groups the densest area of new bone was in the area of the anchoring and sealing callus. The bridging callus contained trabecular bone that was often interspersed with areas of hypertrophic cartilage undergoing resorption. The most delicate trabeculae--comprised of one to two lamellae, often with cartilage cores--were seen in the uniting callus.

Table 2 summarizes the statistical results of both replicates at each field strength. The mean healing index for the animals exposed to 5000 V/m unquestionably was less than that for the corresponding control animals ($p << 0.001$). Also, in all individual categories of comparison, with the exception of alignment, the experimental fractures were significantly less advanced ($p < 0.01$).

In the individual measures of fracture healing, the experimental animals exhibited a tendency toward more variability, as evidenced by the percent standard deviations listed in Table 2. This was significant, however, in only three cases. Because its mean value is the sum of the means of each parameter but its standard deviation (and therefore its percent standard deviation) is not the sum of the individual standard deviations, this trend is not reflected by the healing index.

The increased amounts of cartilage and the scarcity of new bone in the fractures exposed to 5000 V/m indicated a relatively immature stage of fracture repair. By comparing the observed healing in the experimental animals with the normal temporal sequence of repair of the particular fibular fracture (Cullen et al., 1978), we estimate that the 14-day field-exposed fracture resembled the normal fracture site at perhaps 10 days after fracture.

DISCUSSION

The ability to heal injury is one of the preeminent characteristics of living things. We found that this process is adversely affected by electric fields of 5000 V/m. Fracture healing, as opposed to healing in other tissues, is a true regenerative phenomenon. It results in the elaboration of material identical in structure and composition to the original. The data establish, therefore, a link between exposure to fields of 1000 to 5000 V/m and fracture healing but not necessarily a link with nonregenerative healing.

For some biological parameters, such as reaction time, body or organ weight, or mitotic index, it is not possible to categorically

TABLE 2

Comparison of Histological Gradings of Experimental and Control Animals*

Criterion	Replicate 1		Replicate 2	
	Control	Experimental	Control	Experimental
	Exposure Level of 5000 V/m			
	n = 17	**n = 18**	**n = 20**	**n = 20**
Union	5.3 ± 0.9	4.2 ± 1.0†	5.4 ± 0.8	4.4 ± 0.8†
Alignment	1.9 ± 0.3	1.4 ± 0.7	1.6 ± 0.7	1.4 ± 0.8
Callus size	2.9 ± 0.8	1.9 ± 0.8†	3.0 ± 1.0	2.0 ± 0.9†
Anchoring callus	8.2 ± 1.8	5.2 ± 1.2†	8.2 ± 1.5	4.6 ± 1.4†
Bridging callus	6.8 ± 1.9	4.0 ± 0.9†	6.7 ± 1.5	3.9 ± 1.2†
Uniting callus	7.0 ± 2.1	3.8 ± 1.2†	5.6 ± 1.2	3.7 ± 0.9†
Seating callus	7.3 ± 2.0	4.6 ± 1.5†	6.8 ± 1.1	4.2 ± 1.7†
Healingindex‡	39.3 ± 7.7	25.2 ± 3.5†	37.2 ± 6.1	24.0 ± 3.2†
Percent deviation in				
Union	17	23	14	18
Alignment	17	52†	42	56
Callus size	29	39	36	46
Anchoring callus	22	23	18	31†
Bridging callus	28	22	23	31
Uniting callus	30	32	21	25
Sealing callus	27	31	16	41†
Healingindex‡	20	14	16	13
	Exposure Level of 1000 V/m			
	n = 20	**n = 21**	**n = 21**	**n = 21**
Union	4.7 ± 0.6	5.0 ± 0.5	5.0 ± 0.4	5.0 ± 0.6
Alignment	1.3 ± 0.9	1.4 ± 0.7	1.7 ± 0.6	1.7 ± 0.6
Callus size	2.2 ± 0.9	2.3 ± 0.7	1.9 ± 0.7	1.8 ± 0.8
Anchoring callus	5.4 ± 1.9	5.6 ± 1.8	7.0 ± 1.7	8.0 ± 1.3
Bridging callus	4.6 ± 1.4	5.0 ± 1.1	5.0 ± 1.1	5.3 ± 1.0
Uniting callus	4.6 ± 1.0	4.4 ± 1.1	4.4 ± 0.8	4.7 ± 1.4
Sealing callus	4.9 ± 1.4	4.6 ± 1.7	4.0 ± 1.4	4.5 ± 1.8
Healing index	27.9 ± 4.3	28.3 ± 3.6	29.0 ± 3.0	30.9 ± 3.8
Percent deviation in				
Union	12	10	8	11
Alignment	67	48	33	35
Callus size	38	31	39	47
Anchoring callus	34	33	24	16
Bridging callus	29	21	22	18
Uniting callus	22	24	18	29
Sealing callus	30	36	35	39
Healing index	15	13	10	12

*The means and standard deviations are listed. The means in each category in both replicates at 5000 V/m are significantly different ($p < 0.01$), except for alignment.

†Probability, $p < 0.01$.

‡For healing index, $p < 0.001$ ($t = 6.889$ in replicate 1, and $t = 8.601$ in replicate 2).

assert whether a field-induced change to a greater or a smaller value is good or bad for the organism. The impact of healing retardation, however, is clearly adverse from a clinical viewpoint. Even so, the retardation may be reversible. We have obtained data only at 14 days after fracture, and the question of the permanence of the observed changes can be answered only by further work involving longer postfracture periods. On the other hand, the minimum exposure period required to produce retardation at 14 days after fracture also remains undetermined.

On their face, our results are consistent with both the stress hypothesis and the view that they occurred as a consequence of a direct effect on the cells and matrix of the healing system. We believe that stress is the most parsimonious explanation because it proceeds via established physiological pathways and does not incorporate speculative physical mechanisms, and also because it permits a nexus between our results and many seemingly diverse effects reported by others.

Because retardation in fracture healing has been observed in rats exposed to electric fields, the question of the applicability of these results to human beings arises. It might be argued that, since a rat has an ellipsoidal shape, walks on four feet, is almost completely covered with hair, or exhibits some other feature in contrast to that of a human being, it therefore receives a different dose in the same external electric field. We cannot find, however, any clear support for this view. Consequently, since we are unaware of any salient differences in bone physiology between human beings and rats, we believe it is reasonable to assume that corresponding effects would occur in human beings comparably exposed at 1000 to 5000 V/m.

We observed an effect at 5000 V/m but not at 1000 V/m. Our experiments illustrate, we believe, the inadmissibility of applying the threshold concept to observed changes in biological systems. In our view, fields produce biological changes by the same generalized mechanism as heat, cold, crowding, trauma, or any other nonspecific physical entity that can produce debilitating effects in appropriate circumstances. There is no specific mechanism of action which underlies field-induced bioeffects arising from stress. Rather, there is an integrated series of physiological alterations which depend on the instantaneous physiological condition of the individual organism, which may or may not be sufficiently severe to impact on the particular parameter measured. There is obviously a finite capacity in a test organism to resist insult-manifest no effect at a specific level of the dependent parameter. This ability, however, is a function of the general physiology and environment of the test animal. If all the animals in the 1000 V/m experiment, for example, had also been

subjected to a mild cold stress, it is possible that alterations in fracture healing would have been observed in the field-exposed group. Although it is correct, therefore, that the threshold for an adverse effect on fracture healing was between 1000 and 5000 V/m under the conditions used, the field strength at which an effect is manifested under more severe environmental conditions, or in animal populations with different predispositions, may be lower.

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