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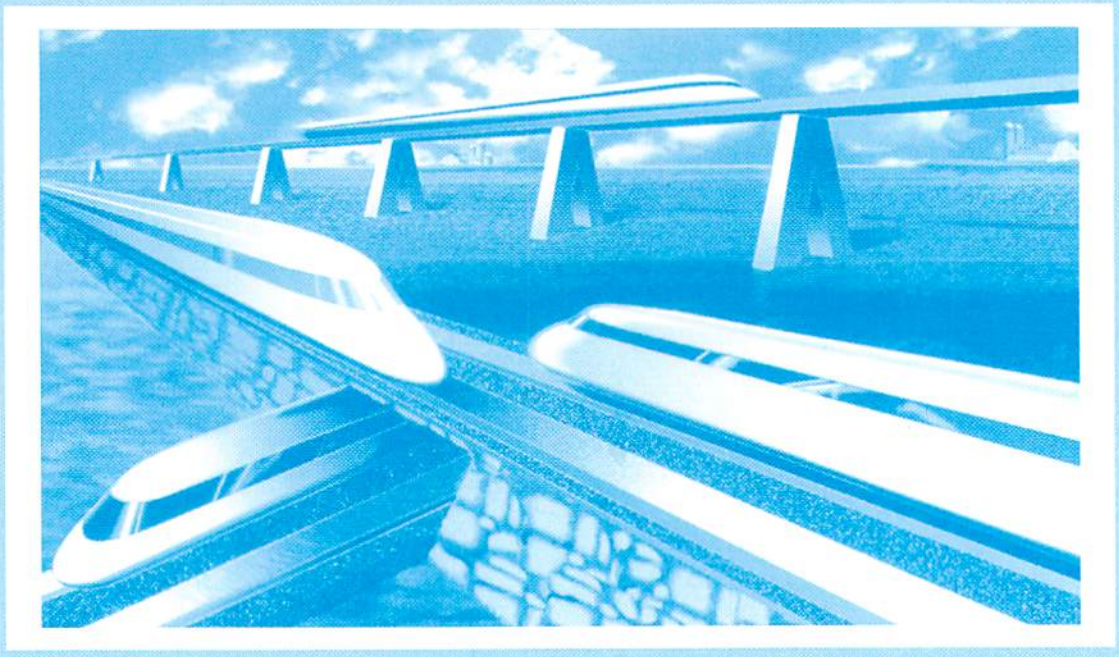
The Biological Effects of Maglev Magnetic Field Exposures



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13. ABSTRACT (Maximum 200 words)

This report describes selected biological effects on transformed human cell lines and on rats from exposure to simulated maglev magnetic fields (MFs). Rats (n = 6 per group) were exposed at various times throughout the 24-h day to MFs simulating the dc and complex ac components of the German TransRapid TR-07 maglev prototype vehicle. Expected ride times as long as 4 h and MF intensities from 50-1500 mG measured for the TR-07 were tested, up to MF levels predicted for superconducting magnet-powered maglev vehicle compartments (1 mG-1.75 G). Maglev-like MF exposures up to 7 times the intensity produced by the TR-07 had no effect on cultured growth of four human cell lines or on chemically induced differentiation compared to control, unexposed cultures. Changes in the amount of rat pineal melatonin and serotonin-N-acetyltransferase (NAT), which have been shown by others to be decreased under a range of eletromagnetic field (EMF) exposure frequencies and intensities, were not observed for TR-07-like MFs. Intermittent exposure to de-component maglev MFs (1-2 G) significantly depressed nighttime (control) levels of NAT, with weak effects on melatonin and NAT seen with 1- to 2-G-intensity intermittent (ac component alone) and continuous maglev (ac + dc) MF exposures. These results should be further examined, since they suggest that ac component TR-07-like MFs and time-varying EMFs at superconducting maglev intensities produce biological effects.

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PREFACE

Since the early 1960's, researchers in the U.S. and elsewhere have been exploring the possibility of using magnetically levitated vehicles for high-speed transportation. Germany and Japan have successfully developed and tested prototypes; and in 1990, the United States launched its National Maglev Initiative to study options for the use of maglev technologies in this country. As a result of growing public concern over exposure to electric and magnetic fields (MFs), research, sponsored by the Federal Railroad Administration (FRA), is being conducted into the possible negative health effects of exposure to MFs, such as those associated with maglev trains.

The purpose of this study was to simulate the magnetic fields that passengers and railway workers could be exposed to during normal operation of the German TransRapid TR-07 maglev electromagnetic attractive system (EMS) vehicle. This report describes the investigation of selected biological effects on transformed human cancer cell lines, and rats, resulting from exposure to simulated MFs. The simulated maglev magnetic fields and their individual AC and DC components were tested at and above those MF intensities measured in the passenger compartment of the TR-07 vehicle.

This work was sponsored by the Federal Railroad Administration (FRA), U.S. Department of Transportation (DOT), under interagency agreement DTRS-57-90-X-00103. Special thanks are extended to the FRA sponsor, A. Bang; the EMF program manager and technical monitor, A. Brecher of the John A. Volpe National Transportation Systems Center, Cambridge, Massachusetts; and I. Gyuk of the Department of Energy (DOE), Office of Utility Management, Conservation and Renewable Energy, for technical guidance and encouragement.

The author thanks R. Reiter of the University of Texas, Health Science Center, San Antonio, and E. Huberman, Argonne National Laboratory (ANL), for numerous conversations and collaboration on this project. Electromagnetic field design and dosimetry support by J. Hull and T. Mulcahy of ANL is gratefully acknowledged. The author benefitted from numerous conversations with M. Misakian, National Institute of Standards and Technology (NIST), regarding technical aspects of electromagnetic field characteristics and measurement. Excellent technical support for this project came from S. Kramer, P. Klingensmith, C. Chubb, M. Jirka, L. Smith, and L. Barlow-Walden. Software support for field generation was provided by S. Basinger, J. Almer, C. Fox, and J. Blomquist. The author thanks D. Grdina, M. Bhattacharyya, and H. Coffey of ANL for encouragement throughout this project and critical review of the manuscript. Editorial comments and assistance by D. Nadziejka are gratefully acknowledged.

SYSTÈME INTERNATIONAL (SI) UNIT DEFINITIONS AND CONVERSIONS USED IN THIS REPORT

DISTANCE (ENGLISH-TO-SI CONVERSION):

1 inch (in)	= 2.54 centimeters (cm)	= 0.025 meters (m)
1 foot (ft)	= 30.5 centimeters (cm)	= 0.305 meters (m)
1 yard (yd)	= 91.4 centimeters (cm)	= 0.914 meters (m)
1 mile (mi)	= 1.61 kilometers (km)	= 1,610 meters (m)

ELECTRICAL QUANTITIES:

Electric Fields

1 Volt/meter (V/m)	= 0.01 Volts/centimeter (V/cm)
1 kilo Volt/meter (kV/M)	= 1000 Volts/meter (V/m)
1 kilo Volt/meter (kV/m)	= 10 Volts/centimeter (V/cm)

Magnetic Flux Densities (English-to-SI Conversion)

10,000 Gauss (G)	= 1 Tesla (T)
10 milliGauss (mG)	= 1 microTesla (μT)
1 milliGauss (mG)	= .1 microTesla (μT)
0.01 milliGauss (mG)	= 1 nanoTesla (nT)

Electromagnetic Frequency Bands

1 cycle per second	= 1 Hertz (Hz)
1,000 cycles per second	= 1 kiloHertz (kHz)

Ultra Low Frequency (ULF) Band	= 0 Hz to 3 Hz
Extreme Low Frequency (ELF) Band	= 3 Hz to 3 kHz
Very Low Frequency (VLF) Band	= 3 kHz to 30 kHz
Low Frequency (LF) Band	= 30 kHz to 300 kHz

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1. EXECUTIVE SUMMARY

The purpose of this study was to investigate biological effects of the magnetic fields (MFs) that passengers and railway workers could be exposed to during normal operation of the German TransRapid TR-07 maglev electromagnetic suspension (EMS) vehicle, proposed for application in the United States. The ability of these MFs to produce biological effects was measured in terms of maglev MF-induced alteration of pineal indoleamine metabolism in rodents. Depression of melatonin and, its precursor, serotonin-*N*-acetyltransferase (NAT) levels in rodents has been a sensitive indicator of electric and magnetic field (EMF) exposure at intensities as low as that of ambient DC MF levels. Power-frequency electric and magnetic fields present in occupational and residential environments have also depressed nighttime levels of melatonin and NAT.

The biological effects of electromagnetic field (EMF) exposure measured in cells were changes in culture growth and differentiation of human leukemia immunological lines, which have been reported as reproducible responses to EMF exposure. Transformed human epithelial cells and human neuroblastoma cell cultures were also exposed to maglev MFs, in order to investigate similar responses.

Simulated maglev magnetic fields and their individual AC and DC components were tested at intensities measured in the passenger compartment of the TR-07 vehicle, as well as at stronger fields. Continuous TR-07 maglev MFs for up to 4 hours (h); at intensities between 1 and 7 times (1X and 7X, respectively) the TR-07 levels; and in the same direction or inverted to the ambient DC MF were produced by a Helmholtz coil. Transient MFs and induced current were also tested for their ability to alter the normal levels and daily rhythms of melatonin and NAT.

MF exposures at up to 7X TR-07 intensity had no effect on cellular growth or differentiation processes in the four types of human cancer cell lines used in this study. Neither continuous nor intermittent MF exposures for up to six days altered their normal differentiation or de-differentiation.

In the animal studies, TR-07 MF exposures for up to 4 h had no effect on melatonin or NAT metabolism, but intermittent DC MF exposures at 7 times the level produced by the TR-07 maglev vehicle did significantly depress NAT. Additional, but not statistically significant, decreases in melatonin and NAT were observed when rats were exposed to continuous maglev AC + DC MFs and to intermittent 7X TR-07 AC maglev fields (10 major maglev frequencies between 1 and 2000 Hz).

These effects replicate those found in other studies that have demonstrated intermittent DC MF effects on the pineal gland, and they suggest that, although TR-07-level MF exposure did not produce changes under the conditions of this study, other types of maglev and electrified transportation systems could produce MFs having intensities, durations, and frequencies that do produce biological effects.

The significance of these biological effects and health consequences to humans is uncertain at our current level of understanding. Since associations between EMF exposure and cancer have been advanced by a number of epidemiological studies and have drawn public attention and concern, maglev and electrified transportation systems should be included as one of the many existing sources of EMF exposure that require continued evaluation.

2. INTRODUCTION

2.1 ELECTROMAGNETIC FIELDS FROM ELECTRICAL TRANSPORTATION SYSTEMS AND THEIR HEALTH EFFECTS

The possibility of using magnetically levitated vehicles for high-speed ground transportation has been examined since the early 1970s, primarily by Germany, Japan, Canada, and the United States. Promising an efficient mode of transportation which could complement short airplane commuter flights in the range of 1000 km [1] and traveling at speeds up to 500 km/h, these vehicles could provide excellent service between cities and major airport hubs.

Germany and Japan have developed and tested prototype maglev systems: the Japanese, using both repulsive superconducting magnets (SCM) and electromagnets with short stator technologies; and the German TransRapid TR-07 attractive maglev system, using conventional electromagnets for levitation and propulsion. The Japanese expect to demonstrate one of their SCM designs by the mid-1990s, and final plans are underway to install a 22 km maglev transportation system in Orlando, Florida, in the same time frame. The National Maglev Initiative (NMI), led by the Federal Railroad Administration (FRA) and supported by the Army Corps of Engineers (ACE) and the Department of Energy (DOE), was initiated in 1990 to explore the options available for using this technology in the United States.

The public began to have health concerns about exposure to electric and magnetic fields (EMF) from electric power lines and devices in the late 1960s. By the mid-1970s, human health concerns associated with extremely low frequency (ELF) EMF had become the focus of attention as a result of the increasing use of extra-high voltage transmission lines. Fear increased over the potential adverse health effects of the electric and magnetic fields produced by transmission and distribution lines, and neighborhood substations. Additional concerns were raised over television and radio interference, audible noise, and induced shocks from touching metal objects in the vicinity of transmission lines [2]. Magnetic fields (MFs) of similar magnitude to those associated with power lines are used to levitate and propel maglev vehicles, as well as public transit and commuter rail.

While electromagnetic field (EMF) effects are believed by many to be a potential human health problem, others dismiss the large number of diverse biological effects attributed to electromagnetic field exposure as unlikely or impossible. They argue that, first, ELF EMF fields do not break chemical bonds as does ionizing radiation (ultraviolet and shorter wavelengths [$< 3 \times 10^{-7}$ m] and higher frequencies [$> 10^{15}$ Hz]). Second, EMFs do not cause tissue heating and subsequent increased temperature effects as do radiofrequency and microwaves. And third, electric fields naturally generated by the body are large compared to those induced by power frequency EMFs. In addition, the body has large electrical resistances at the membranes between cells. Both the internal electric fields plus the large intercellular resistance tend to minimize the possible induced currents from external

electromagnetic fields and the likelihood of significant biological effects [3, 4, and 5]. However, a growing number of epidemiology studies support a relationship between typical environmental and electrical-occupational EMF exposure and cancer incidence or mortality, while laboratory studies add to the number of reproducible biological effects produced by externally applied electromagnetic fields in the extremely low frequency range of 3−3000 Hz [2].

Even though a diversity of changes attributable to electric and magnetic electromagnetic field exposure have been demonstrated in cells and animals [2, 4, 11, 12, and 13], our present lack of understanding of nonionizing ELF biological effect mechanisms makes it difficult to interpret the significance of these changes and extrapolate them to adverse human health consequences.

Electromagnetic fields produced by maglev and other electrified rail systems had not been measured until the Federal Railroad Administration (FRA)-sponsored study of the ELF electric and magnetic fields produced by the German TransRapid TR-07 maglev vehicle [6, and 7], and by a number of other electric-powered transit and rail transportation systems.

From available information about the electromagnetic fields produced by maglev and electric-powered vehicles, the majority of magnetic fields are DC and in the ELF range. The intensities vary with time and location, and depend upon the specific transportation system characteristics, as well as the level of power use and speed of the vehicle. In superconducting maglev vehicles, DC fields could reach upwards of 150 G, with current limits placed at less than 10 G, and AC field magnitudes of up to 1G possible in the passenger compartment [8 and 9]. In addition, it is likely that time-varying dc, power frequency (50−60 Hz), and transient ELF magnetic field components will be encountered.

Which parts of this very complicated EMF spectrum will prove to be causally related to any specific health hazard is unclear at this time, but these transportation systems do have EMF field emissions in the frequency and intensity ranges which have been demonstrated to have biological effects in cell, animal, and human studies. No significant adverse health effects have been consistently identified in the few epidemiological studies that have examined transportation system passengers or workers for biological responses to EMF exposure [8].

2.2 BACKGROUND

2.2.1 Cell Studies of EMF Biological Effects

Cellular studies have shown changes in ion flux across the cell membrane [10 and 11]; changes in nucleic acid transcription and translation patterns [12, 13, and 14]; changes in normal cell responses to hormones, neurotransmitters, and growth factors [15, 16, 17, and 18]; changes in immunological response, such as depression of NK

cell activity [19] or suppression of T-lymphocyte cytotoxicity [20]; and changes in cancer cell growth kinetics [21, 22, 23, and 24].

2.2.2 Animal Studies of EMF Biological Effects

Animal studies of EMF bioeffects have been extensive: the most significant and repeatable EMF effects have been in the areas of perceptual, behavioral, and neuroendocrine effects, including changes in chronobiological rhythms. The suppression of pineal melatonin and serotonin-*N*-acetyltransferase (EC 2.3.1.5; NAT) has been one of the most reproducible responses to nonionizing EMF exposure. In addition to the pineal being a light-sensing organ in lower vertebrates, its circadian and seasonal rhythms provide a time-of-day cue for most cells and organ systems in the body, and this helps to keep the animal "tuned in" to its environment [25 and 26].

Melatonin depression by EMF exposure was demonstrated in humans by Wilson et al. [27], who, in a pilot study, found a decrease in the urinary melatonin metabolite 6-hydroxy-melatonin sulfate at night in females who used high-current electric blankets (relative to subjects using low-current electric blankets). There was a range of responses to the continuous polymer wire (CPW) blankets, suggesting there were individual sensitivity differences to power frequency exposure. Since melatonin has been shown to inhibit the growth of breast tumor cell lines in vitro [28], EMF depression of pineal melatonin has been proposed as a possible mechanism to explain the epidemiological evidence which suggests that EMF exposure may increase breast and prostate cancer risk, as well as leukemia [29].

Wilson et al. [30] demonstrated a greater than 50% depression in the nighttime pineal melatonin levels in rats by continuous exposure to a 100 kV/m 60 Hz electric field for three weeks. However, the rhythm returned after exposure ended. In later studies with 60 Hz electric field exposures as low as 1.7 kV/m, Wilson showed the same depression in melatonin and in NAT, the regulatory enzyme in the metabolic pathway from serotonin to melatonin in the pineal. A phase delay of approximately 2 h in the melatonin circadian rhythm was also produced by the electric field exposure [29]. Vasquez et al. [31] repeated these results and showed that rats exposed to 39 kV/m, 60 Hz electric fields exhibited phase shifts of up to 4 h in the circadian rhythms of the neurotransmitters norepinephrine, dopamine, and the serotonin metabolite 5-hydroxyindoleacetic acid in the hypothalamus, striatum, and hippocampus.

Not only have environmental levels of DC and AC magnetic fields produced depression in circadian neurotransmitter rhythms, but rapidly changing magnetic fields of low, ambient intensity have shown similar neurotransmitter effects. Lerchl et al. [32 and 17] showed that intermittent reversal in the polarity of earth-strength, DC MFs for 1 h depressed normal melatonin and NAT rhythms in the rat pineal. The effect was observed when fields were rapidly switched, but not when reversal was done slowly over several seconds. This suggests that transient fields, that produce induced currents in exposed cells and animals, may contribute to EMF biological responses.

2.3 PURPOSE

The purpose of this study was to examine the potential biological effects on cells and rodents that result from exposure to the complex-spectra, time-varying EMF fields produced by maglev transportation systems that use conventional electromagnet technology. Maglev MFs were simulated based on the TransRapid TR-07 maglev spectra measured by Electric Research and Management, Inc. (ERM), [6 and 7]. In cellular and animal systems, the MF exposures used are those likely to be encountered by maglev and electric transit passengers and workers, as well as MF conditions that have produced reported repeatable biological effects using power frequency or static DC magnetic fields.

3. EXPERIMENTAL METHODS

3.1 MAGNETIC FIELD GENERATION

The background DC magnetic field of the exposure room was measured and the DC magnetic fields during exposures were monitored using a gaussmeter with a Hall effect probe (F.W. Bell, Model 610, Orlando, Florida). The geostatic magnetic field declination was approximately 0° (i.e., the horizontal component of the geostatic field pointed toward the geomagnetic north pole) and the inclination was 55°, with the magnitude of the total field H = 0.039−0.042 mT (390−420 mG), i.e., the horizontal component was 224−241 mG and the vertical component was 319−344 mG.

A pair of Helmholtz coils 1 m in diameter and 0.5 m apart were fabricated for animal exposures. Each coil consisted of 300 turns of 20-gauge copper wire, and the combined Helmholtz coil was supported on a wooden frame to minimize vibration when energized. The inductance of the coils was determined to be 0.52 H, with a time constant of 8.1 ms (resistance = 64.2 Ω).

The Helmholtz coil was used as a search coil to measure the background AC component of the magnetic field. AC field frequencies and intensities were verified using a 3566A personal computer (PC) Spectrum/Network Analyzer (Hewlett-Packard, Cupertino, California). The maximum AC field was 0.26 mG rms at 60 Hz. The magnetic field at other frequencies was substantially lower, and the maximum intensity over a 0- to 500-Hz bandwidth was 0.98 mG rms.

A bipolar power supply (Kepco, Flushing, NY, Model BOP 50-2M, ±50 V, 0−2 A) was used to energize the Helmholtz coil system to create magnetic field (MF) exposures. The simulated maglev magnetic field MF (DC and multi frequency, sinusoidal ac) spectrum was generated using a 286 personal computer and LabWindows Data Acquisition and Analysis software (National Instruments, Austin, Texas). The program developed is capable of producing a DC and/or multifrequency AC signal to the bipolar power supply (of up to 10 individual frequency and intensity components) in the range of 0−2 G (dc) and 0−2 kHz (ac). The AC field generated by the Helmholtz coils was measured with a smaller search coil with an area of 0.28 m^2. The AC intensity over 0−2 G range was within 1% of the expected values, and the computer-generated frequency over the 0−2 kHz range was accurate to within ±1 Hz.

The ramp rate of the signal can be varied over a wide range (microseconds to seconds) to vary dB/dt. This is especially useful in exploring the effects of ramp rate on periodic DC signals. The power supply applies a voltage to the leads of the Helmholtz coil, and the DC current is determined by the total resistance of the system. The ramp rate is determined by the inductance and resistance of the coils, and, as was measured, to a small extent by the response time of the power supply (Figure 3-1). Ramp rates faster than the natural time constant were obtained by

initially applying a much higher voltage than the steady-state value and then ramping down to the steady-state value.

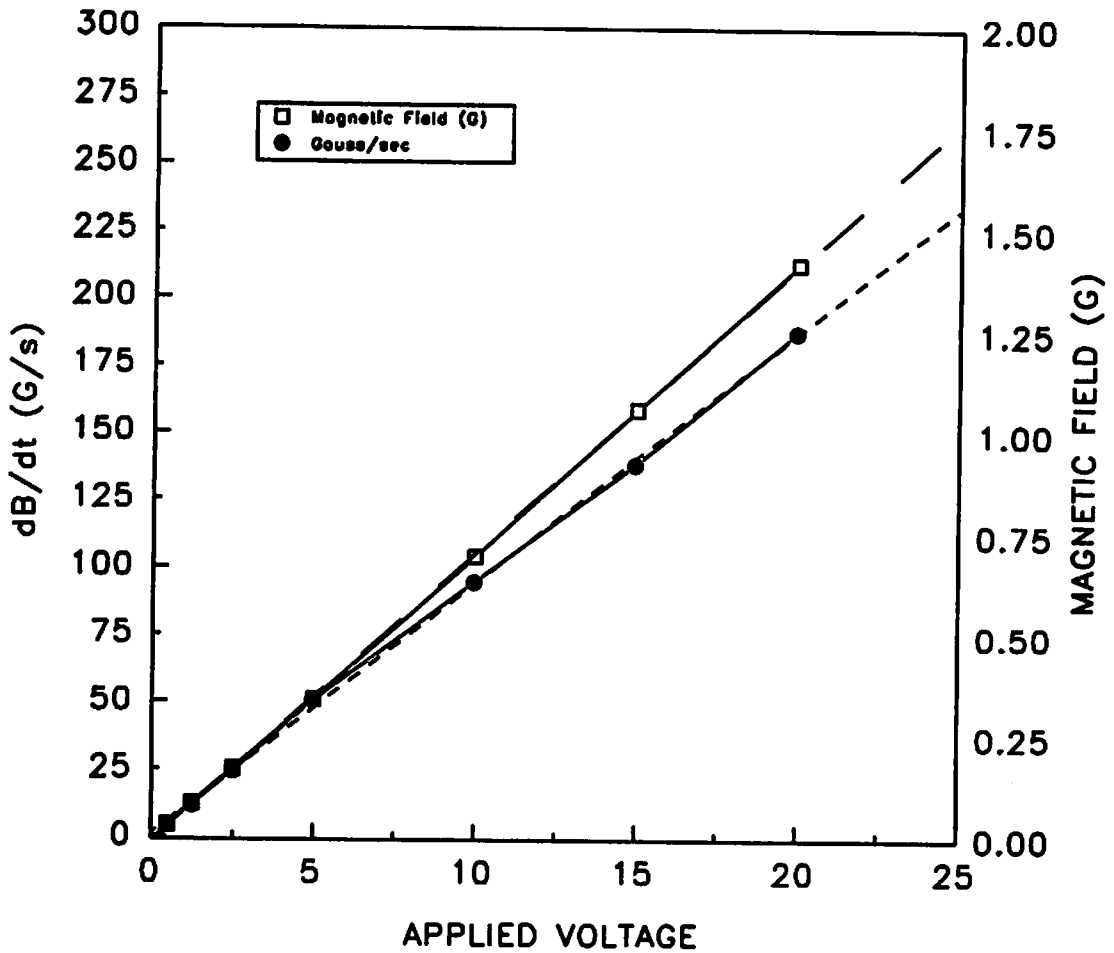


FIGURE 3-1. **MEASURED HELMHOLTZ COIL DC FIELD CHARACTERISTICS.** Magnetic field (G, open box) and dB/dt (G/s, closed circle) produced by exposure within a pair of Helmholtz coils for an applied voltage.

Intermittent MF exposures could be programmed to turn on and off at specified times; the start time and length of the exposure is also programmable, producing an induced voltage in the Helmholtz coil and subsequent eddy currents in exposed cell cultures and animals.

The magnetic field generated by the Helmholtz coils was mapped three times over the 12-month period of these experiments. For the areas in which biological specimens were exposed to MFs in the Helmholtz apparatus, the average value of the MF in the exposure area was 100.7% ± 7.5 (mean ± S.D.) from the value measured at the center of the Helmholtz coil, and 98.9% ± 9.9 in the cell exposure facility.

3.2 MAGNETIC FIELD EXPOSURES

Maglev magnetic field exposures were simulated from spectra collected inside a moving (168 km/h) passenger compartment of the German TransRapid (TR-07) maglev prototype vehicle, as measured by Electric Research and Management, Inc. in August 1990 [7]. Figure 3-2 depicts the complex AC spectrum of this prototype maglev vehicle. Different, but analogous, spectra are likely to be produced by superconducting maglev and other electrified transportation systems. The DC component of the TR-07 was 250 mG above ambient. Although the AC and DC MF intensities, and especially the transient profiles, are unique to the system for the TR-07 and for other existing and proposed electromagnetic- and electrodynamic-MF maglev vehicles, they are all expected to produce similar magnetic field profiles. However, these profiles will be quite different from the DC, 60 Hz, and other individual- and multi-frequency-AC MF sources that have previously been used in biological exposure experiments.

In our experiments, 10 predominant frequencies at TR-07-measured intensities over the 0−2 kHz spectrum, plus a 250 mG DC component, were selected and used to simulate the TR-07 exposure (labeled 1X; Figure 3-3 and Table 3-1). The same frequencies at intensities that are 7-fold greater than those produced in the TR-07 vehicle (labeled 7X) were also tested, because they are well within the intensities measured or expected for the passenger compartment of superconducting-magnet maglev vehicles. Also tested were DC and 60 Hz fields alone, to resolve bioeffects due to each component.

The magnetic field exposures were physically presented in several different ways:

1. Exposure length: 1−4 h (animal experiments)
   1−6 d (cell experiments)

2. Continuous or intermittent (repeating pattern of 45 s on, 15 s off, quickly ramped) MF exposures. The rate of change in field (dB/dt) was 37 (1X) or 267 (7X) G/s. Rapid application of an intermittent, inverted earth-strength static MF has previously been shown to significantly decrease pineal melatonin and NAT [32 and 17].

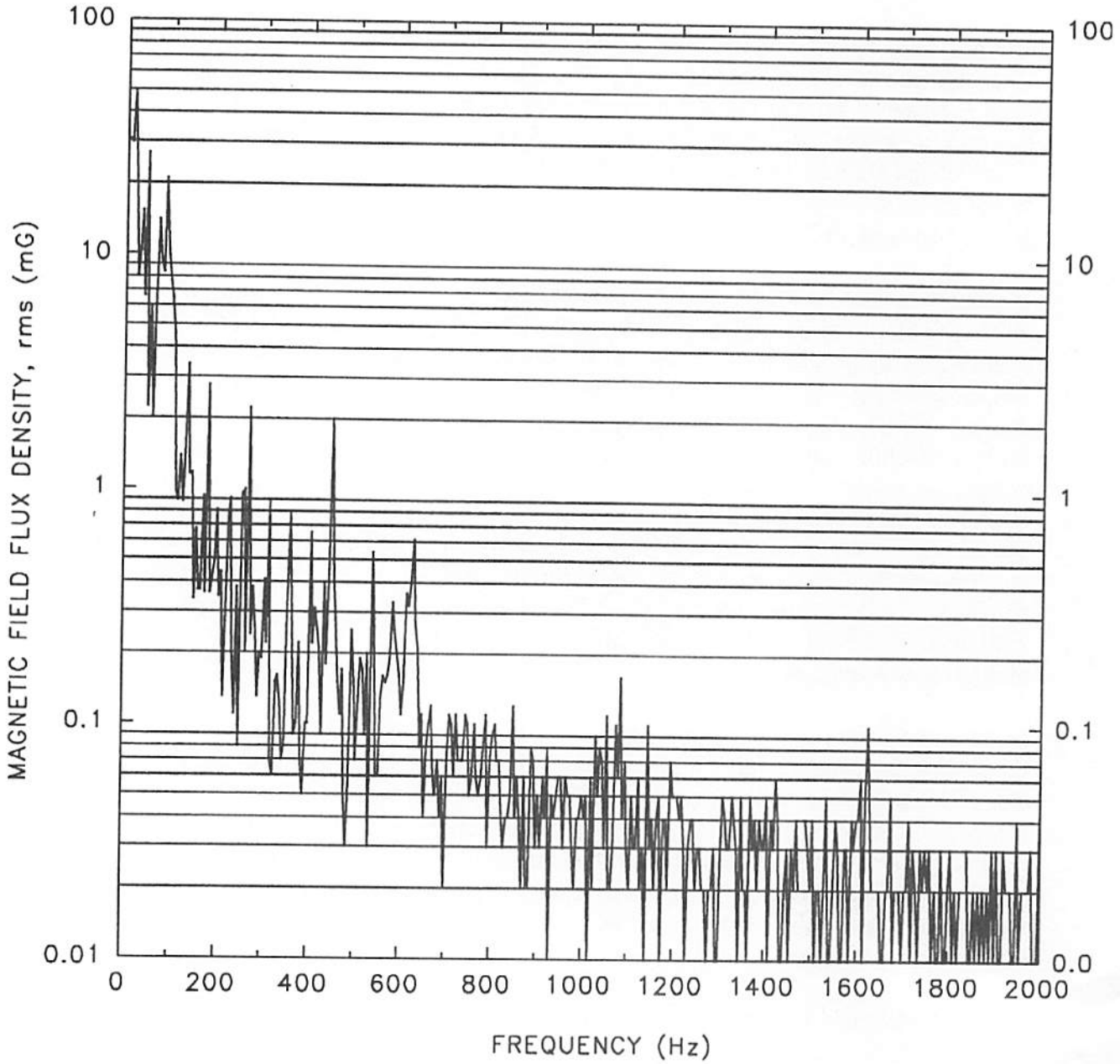
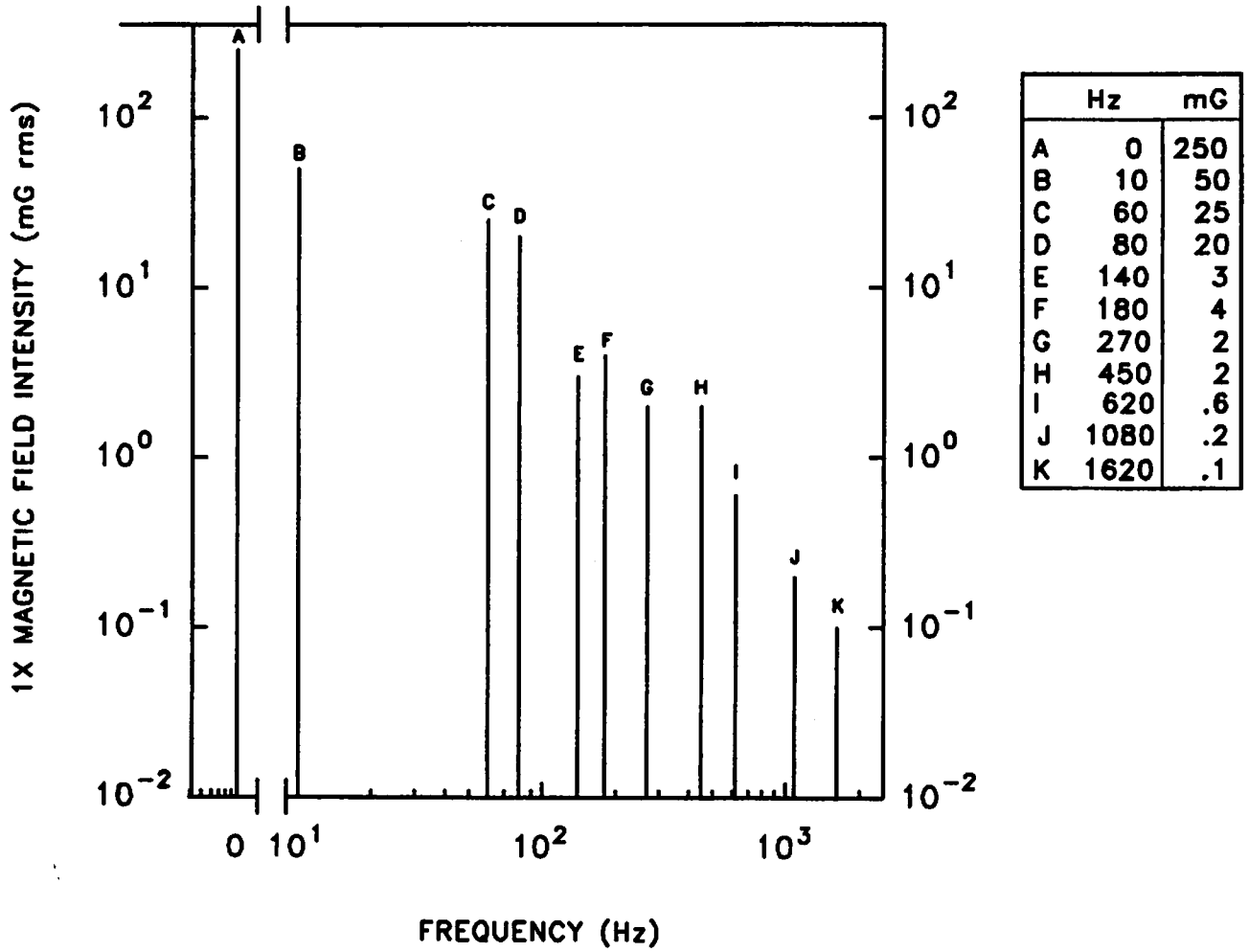


FIGURE 3-2. **TR-07 AC MAGNETIC FIELD SPECTRUM.** Vehicle traveling at 168 km/h. The DC component was 250 mG above the ambient field. Measurement recorded August 1990 by Electric Research and Management (Dietrich et al., 1992)



	Hz	mG
A	0	250
B	10	50
C	60	25
D	80	20
E	140	3
F	180	4
G	270	2
H	450	2
I	620	.6
J	1080	.2
K	1620	.1

FIGURE 3-3. **SIMULATED TR-07 MAGNETIC FIELD.** The prominent frequencies (Hz) and their respective intensities (rms), including a 250 mG DC component, were delivered simultaneously by computer to the Helmholtz exposure apparatus. The entire spectrum was increased 7-fold for the 7X exposures.

TABLE 3-1. SIMULATED TRANSRAPID (TR-07) MAGNETIC FIELD

Frequency (Hz)	Intensity (mG rms)	
	1X	7X
0 (DC)	250.0	1750.0
10	50.0	350.0
60	25.0	175.0
80	20.0	140.0
140	3.0	21.0
180	4.0	28.0
270	2.0	14.0
450	2.0	14.0
620	0.6	4.2
1080	0.2	1.4
1620	0.1	0.7

3. Exposures were to the horizontal ambient MF component or parallel to the inclination of the ambient magnetic fields (55°).

4. Exposures were in the same direction as, or opposite to ("inverted"), the ambient magnetic field.

3.3 CELL EXPOSURE FACILITY

Cell MF exposure experiments were conducted in a Helmholtz coil apparatus which contained a styrofoam incubator of nonferrous (nonmagnetic) material, 36 cm wide × 55 cm high × 32 cm deep (Figure 3-4). Environmental control was provided by a standard tissue culture incubator outside the Helmholtz coils. Air, forced from the incubator through 3-in. insulated plastic hose, maintained 37 °C, 85% relative humidity (RH), and 8% CO_2 in the exposure incubator. Control (unexposed) cells were kept in another standard tissue culture incubator separate from the MF exposure facility. Preliminary experiments demonstrated the same growth rates and final culture cell concentrations in both the control and exposure incubators. The Helmholtz coil and MF-exposure incubator were upright and oriented in a north-south direction, and all experiments in this facility received only horizontal-component North-South MF exposures.

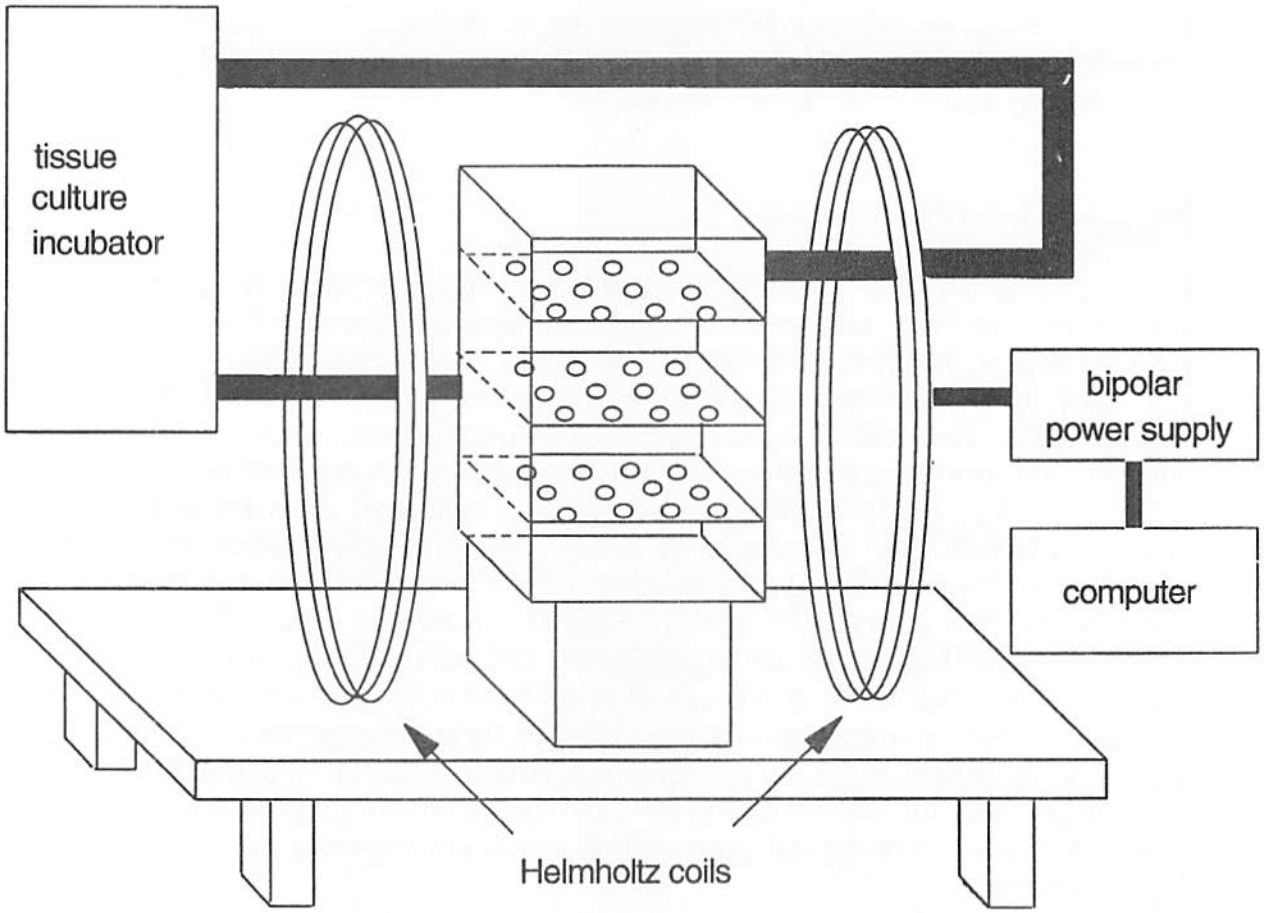


FIGURE 3-4. **CELL EXPOSURE FACILITY.** A non-ferrous chamber was environmentally controlled from a separate tissue culture incubator connected by insulated 3" plastic ducts. The incubator was oriented on a plastic support between the Helmholtz coils (diameter perpendicular to the north-south ambient MF) so that the shelves supporting the petri plates were in the uniform area of the fields.

3.4 ANIMAL EXPOSURE FACILITY

Rats (in groups of six animals) were placed into standard animal facility rat cages that were modified with plastic barriers to allow individual containment and exposure of three rats per cage (Figure 3-5). The exposure cages were placed in the central area of the Helmholtz coils. For exposures, the Helmholtz coil apparatus was oriented so that the field it produced was in the north-south direction, either perpendicular to the floor for horizontal-component MF exposures or perpendicular to the inclination of the ambient static MF for parallel exposures. For sham exposures, control groups were similarly handled, but without applied MF.

3.5 CELL EXPERIMENTS

Four transformed human cancer cell lines, selected because of literature reporting associations with EMF, were exposed to MFs and examined for cell growth changes and alteration of chemically stimulated differentiation (Table 3-2). Cells were inoculated into 60-mm petri dishes at a concentration of 2×10^4 cells/ml in 5 ml of medium (RPMI 1640, GIBCO) containing 15% fetal calf serum, penicillin (100 units/ml), and streptomycin (10 μg/ml), and grown under standard conditions for 24 h (37 °C, 85% RH, 8% CO_2). Exponentially growing cells were either left untreated or chemically induced to differentiate by adding mycophenolic acid (MPA) or phorbol 12-myristate 13-acetate (PMA) at appropriate concentrations, 0.1 μM or 3.0 nM, respectively). The cultures were placed in either the control or the non-ferrous MF-exposure incubator. Previous measurements and culture growth experiments (data not shown) had demonstrated equivalent environmental conditions in the two incubators. Sham exposure (no exposure) experiments in the exposure incubator also showed no differences in culture growth or cell differentiation to MPA or PMA from the incubator used for controls during MF-exposure experiments. Duplicate plates were removed daily and the cell concentration was determined using a hemacytometer.

The horizontal MF exposures were either continuous or intermittent at levels of 1X or 7X maglev levels until the end of exponential growth (4−6 d, depending on initial cell concentration and cell growth rate). Plates were then examined for morphological changes, fixed, and scored for specific surface antigen/immunofluorescent antibody reactivity (HL-60 and CEM) [33], melanin production (SK-MEL-131 melanoma), or differences in cell spreading or dendrite change (SH-SY5Y neuroblastoma). The goal was to determine the extent of cell differentiation in the presence or absence of MPA or PMA and MF-exposure.

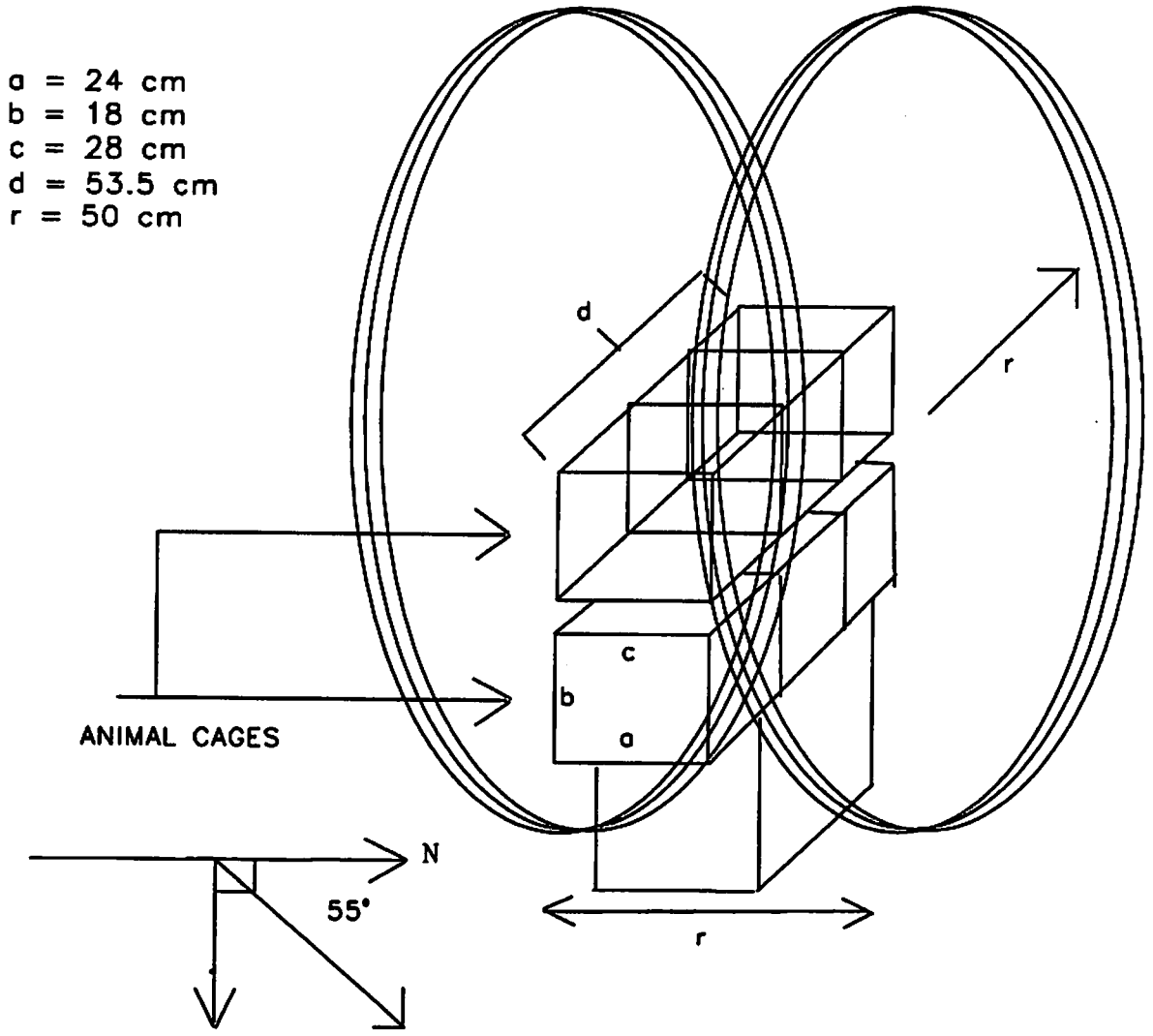


FIGURE 3-5. **ANIMAL EXPOSURE FACILITY.** The Helmholtz coil was oriented with its diameter perpendicular to the north-south ambient magnetic field. Two animal cages on a plastic support were arranged in the center of the coil pair in the area of uniform magnetic field. Each cage was subdivided into three equal portions to allow individual, unattenuated MF exposure.

TABLE 3.2. HUMAN CELL LINES TESTED FOR RESPONSE TO MF EXPOSURE

Human Cell Line	Cell Type	Response Measured
HL-60	Promyelocytic leukemia (monocytic or granulocytic)	OKM1
CEM	T-lymphoblastoid	OKT3
SK-MEL	Skin melanoma	Melanin
SH-SY5Y	Neuroblastoma	Cell spreading dendrites

3.6 ANIMAL EXPERIMENTS

Male Sprague-Dawley (Cobb strain) rats (*Rattus norvegicus*), 44−47 d old, 100−120 g, were purchased from Charles River (Wilmington, Massachusetts). Food and water was available at will and was removed during MF or sham exposures (longest exposure, 4 h). Conditions were constant at 22 °C and 50% RH. For all experiments, animals were entrained for two weeks to a 14:10 light-dark (LD) cycle (dark period [D] = 0500−1500 hours), with dim red light present during the dark portion of the cycle.

Six rats per group were transferred into the modified exposure cages, placed in the Helmholtz coils, and exposed to the magnetic fields. Six similarly treated but unexposed animals served as controls. Table 3-3 outlines the MF exposures tested. Three one-week series of control and MF exposure experiments were run during 1991−1992, using approximately 1000 animals. Different groups of entrained animals were MF exposed daily, for 7 days in each of three experiments during dark for up to 4 h, ending at 5, 6, or 9 h after dark onset. Another group of six animals were exposed for similar lengths of time, ending 5 h after light onset.

Immediately after an exposure, the exposed and control rats were alternately sacrificed quickly and the pineal, hypothalamus, and brain stem were removed and frozen (−60 °C, dry ice, average time 30 s). (Note: this report documents only changes in pineal melatonin and NAT. The results of MF exposures on brain hypothalamus and brain stem neurotransmitters will be analyzed in future work and given in a later report). The lighting conditions during collection of the biological tissues until frozen reflected those present when the MF exposure occurred. The samples were stored at −60 °C until assayed.

TABLE 3-3. MAGNETIC FIELD EXPOSURES

Expt.	MF exp. type	C or I	TR-97 Intensity	Length (h)	Field Direction	Field Orientation
	mag	C	1X	1	+	⊥
	mag	C	1X	2	+	⊥
	mag	C	1X	4	+	⊥
	mag	C	2X	1	+	⊥
I	mag	C	2X	2	+	⊥
	mag	C	2X	4	+	⊥
	mag	C	4X	1	+	⊥
	mag	C	4X	2	+	⊥
	mag	C	4X	4	+	⊥
	mag	C	4X	2	+	⊥
	DC	C	4X	2	+	⊥
	AC	C	4X	2	+	⊥
	mag	I	4X	2	+	⊥
	DC	I	4X	2	+	⊥
	AC	I	4X	2	+	⊥
II	mag	I	4X	2	+	‖
	DC	I	4X	2	+	‖
	AC	I	4X	2	+	‖
	mag	I	7X	2	-	‖
	AC	I	7X	2	-	‖
	DC	I	7X	2	-	‖
	mag	C	1X	2	+	⊥
	mag	C	1X	1	+	⊥
	mag	I	7X	2	-	‖
	DC	I	7X	2	-	‖
III	AC	I	7X	2	-	‖
	60 Hz	I	34X	2	-	‖
	mag	C	7X	2	-	‖

Legend:

C	continuous MF exposure
I	intermittent MF exposure (45 s on, 15 s off)
mag	simulated maglev (AC + DC) TR-07 components
AC	maglev AC only
DC	maglev DC only
*n*X	multiple of TR-07 maglev MF (see Table 1)
⊥	MF horizontal component
‖	parallel to ambient MF
+	same direction as ambient MF
-	inverted to ambient MF
60 Hz	60 Hz only (-840 mg)
ambient	390-420 mG

Pineal samples were coded and shipped to the laboratory of Dr. Russell Reiter at the University of Texas Health Science Center, San Antonio. Melatonin was determined by radioimmunoassay [17]. The assay procedure has been validated by Webley et al. [34]. Serotonin-*N*-acetyltransferase activity was determined by radioenzymatic assay [35]. The results of the assays (with the MF exposures unknown to those performing the assays) were returned to Argonne for data analysis of the effects of MF exposure.

3.7 ANALYSIS OF MF EXPOSURE RESULTS

Differences between control and exposed groups of animals were compared using the two-tailed Student t-test; $p < .05$ indicated statistically significant differences between control and MF-exposed groups.

4. EXPERIMENTAL RESULTS

4.1 CELL STUDIES

In this study, a total of 22 magnetic field (MF) exposure experiments were run, varying the type of MF exposure by intensity, frequency, MF orientation, or MF duration, similar to the range of MF exposures used in the animal studies (see Table 3-3). The MF exposure parameters included TR-07-like maglev (MF, 1X to 7X) or DC only exposures, either inverted or in the same direction as the ambient MF, and intermittent or continuous MF exposures delivered for up to 6 days (through the exponential and into the stationary phase of culture growth, depending on the cell type).

SK-MEL-131 melanoma cells were tested for changes in culture growth melanin production due to the MF-exposure, and SH-SY5Y neuroblastoma cells were tested for any morphological changes and alteration in normal dendrite number or length due to MF exposure. SK-MEL-131 melanoma cells showed no change in growth or melanin production due to the MF-exposure conditions tested, nor were any morphological changes in dendrite formation seen in SH-SY5Y neuroblastoma cell cultures.

The effects of MF exposure on cellular differentiation using HL-60 promyelocytic leukemia and CEM T-lymphoblastoid human cell lines were compared to control cultures, using MPA or PMA to induce differentiation before MF exposure. Maglev or DC MF exposure produced no variation in cell growth or differentiation in the four cell lines compared to control cultures. Typical results are given in Figures 4-1 and 4-2 for CEM T-lymphoblastoid cultures.

The growth kinetics of CEM cells were the same in both the control and MF-exposure incubators, with no significant difference in growth rate or final cell titer (Figure 4-1). Intermittent or continuous 1X or 7X maglev MF-exposure or dc-component alone (1.75 G) for 4 days in the presence or absence of MPA (0.1 μM) also had no significant effect on growth rate or cellular differentiation.

However, exponential growth in CEM cultures treated with PMA (3.0 nM) for 3 days was inhibited (Figure 4-2). MF exposure, however, had no influence on CEM cell growth or differentiation in cells exposed to continuous or intermittent 7X TR-07 maglev MF's relative to control cultures. After 4 d, 20% of both the exposed and control CEM cultures incubated with PMA had differentiated and showed a positive (fluorescent) response to OKT3 antibody. The TR-07 maglev MF exposure had no effect on differentiation under any of the maglev or maglev-component MF exposure conditions tested.

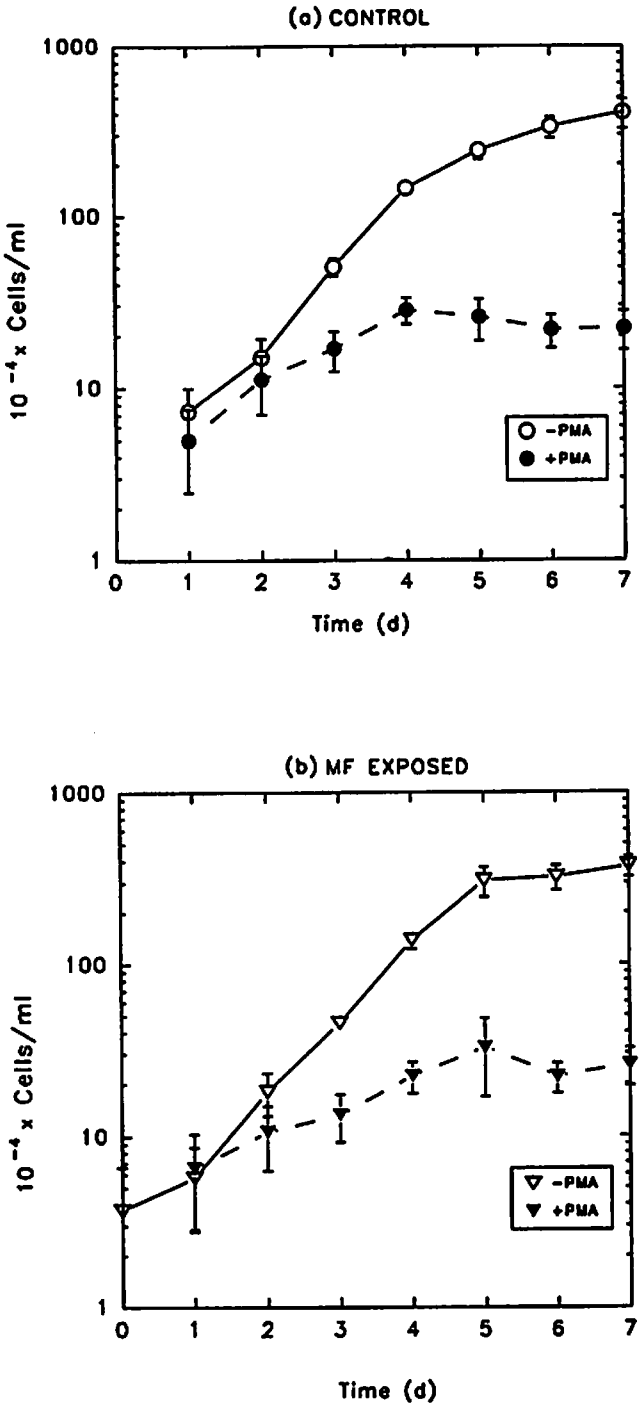


FIGURE 4-1. CEM CELL GROWTH AND MF EXPOSURE WITH MPA. On day 0, MPA (final concentration, 0.1 μM) was added to 50% of the plates, which was incubated for 4 d under control (a) or maglev EMF-exposure (b) conditions. Culture growth was determined by daily hemocytometer counts for duplicate plates. On day 4, duplicate samples were assayed for percentage of differentiation. Closed symbols, MPA-treated; open symbols, untreated; bars = $\pm$ standard deviation.

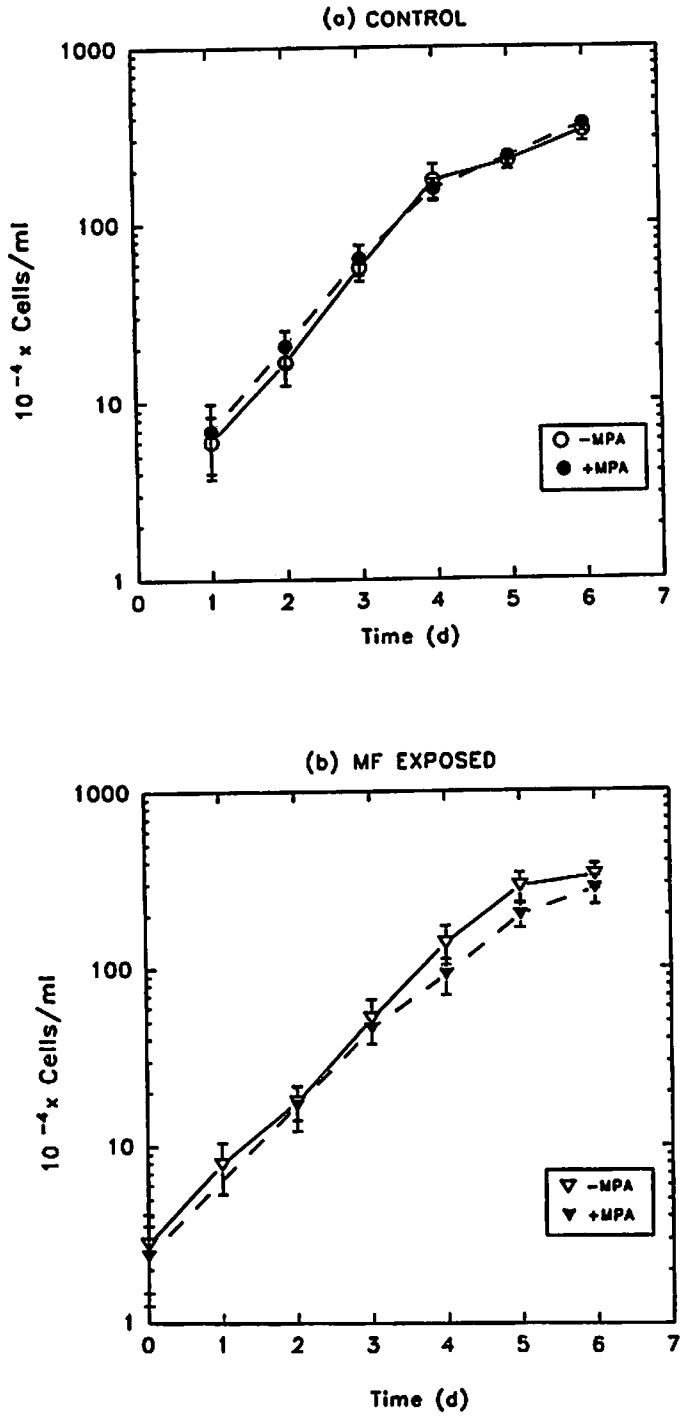


FIGURE 4-2. CEM CELL GROWTH AND MF EXPOSURE WITH PMA. On day 0, PMA (final concentration, 3.0 nM) was added to 50% of the plates, which were incubated for 4 d under control (a) or maglev EMF-exposure (b) conditions. Culture growth was determined by daily hemacytometer counts, in duplicate. On day 4, samples were assayed for percentage of differentiation. Closed symbols, PMA-treated; open symbols, untreated; bars = ± standard deviation.

4.2 ANIMAL STUDIES

4.2.1 Pineal Melatonin and NAT Rhythms

The daily rhythm of pineal melatonin and its regulatory enzyme NAT was determined several times during the course of these MF exposure experiments (Figures 4-3 and 4-4). The timing of maximum pineal melatonin and NAT activity during the circadian cycle in light-dark entrained rats determined which times were chosen for the MF exposures. These standard curves also demonstrated that the entrainment protocol was successful and that the animals had not shifted their melatonin and NAT rhythms. Most MF exposures, which varied in type and duration, occurred during the early 50% of maximum melatonin, with sacrifices at 1000 hours or 1100 hours. Additional MF exposures occurred during the latter 50% of the peak in pineal melatonin, with sacrifices at 1400 hours. For comparison, MF exposures given during dark were repeated at one time in the early light phase, ending at 2000 hours.

When animals were entrained for two weeks to a 14:10 LD cycle and sacrificed every 2 h for 24 h, a strong melatonin rhythm was found. A reproducible 10-fold increase over light-phase levels was observed during the dark phase of the circadian cycle (Figure 4-3). Maximum melatonin levels were seen 4.5 h following the onset of dark; the maximum levels remained for 4 h, with a sharp decline approximately 1 h before the beginning of the light phase. Daytime (L) levels of melatonin were consistently less than 200 pg per pineal.

The corresponding cycle in NAT activity reproducibly had a bimodal peak during the dark phase of the light-dark cycle (Figure 4-4). The first peak occurred 4.5 h after dark onset, at the same time melatonin reached the maximum nighttime level in the pineal. NAT then decreased, and shortly thereafter rose to a 2.5-fold increase in activity over the earlier peak level, reaching maximum activity 8.5 h after the onset of dark. This was followed by a rapid fall to typically low, daytime levels shortly after the onset of light. While NAT activity showed two strong pulses in activity during the 6 h of mid to late dark, pineal melatonin remained at maximum levels.

4.2.2 Simulated TR-07 Exposures (1X)

No significant changes in pineal melatonin levels occurred as a result of simulated TR-07 MF exposure under a number of MF delivery protocols in the three major MF exposure and control experiments run in this study, which tested the effects of type of MF (maglev-like, AC, or DC), frequency, intensity, or MF orientation (Figure 4-5). Continuous MF exposure during dark (maximum melatonin) for 1, 2, or 4 h did not depress pineal melatonin below control levels. Intermittent, inverted TR-07-level (1X) maglev MF exposures (net MF = +150 mG, dB/dt = 37 G/s) for 2 h also had no effect on maximum (dark) melatonin levels.

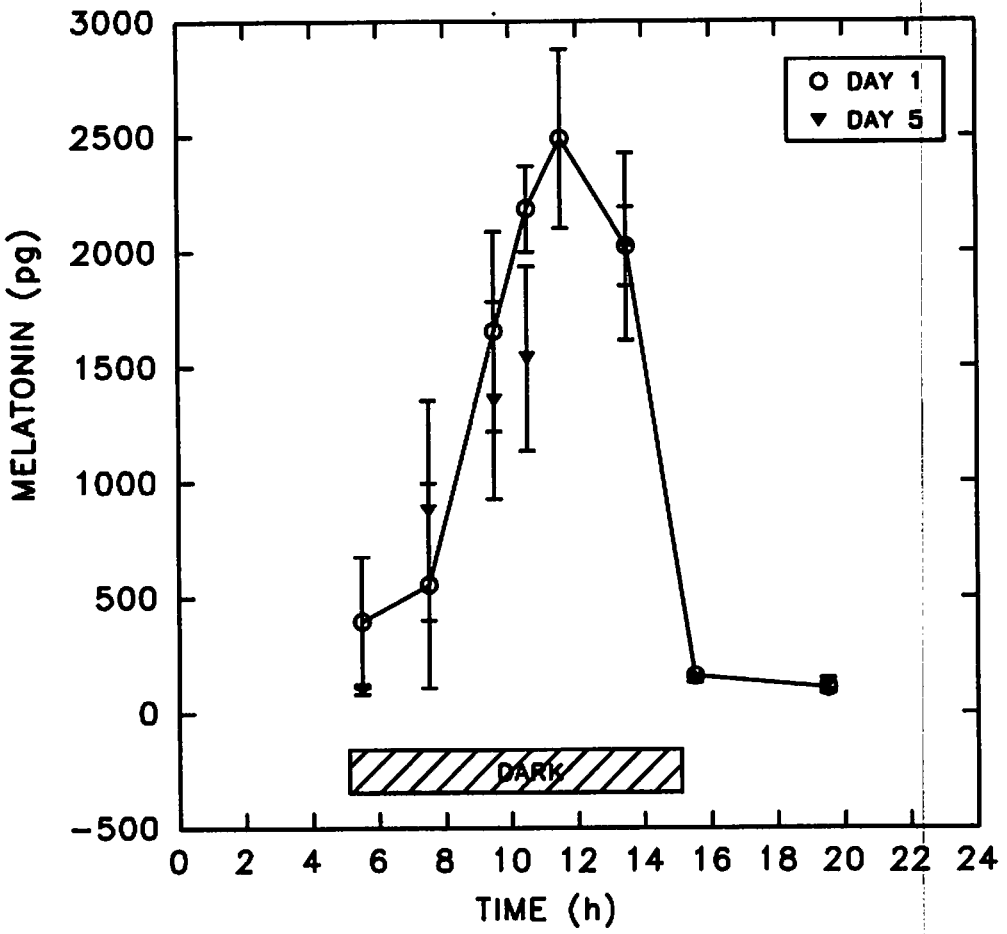


FIGURE 4-3. CIRCADIAN PINEAL MELATONIN RHYTHM. After 2 weeks of LD 14:10 entrainment, rats (six per group) were sacrificed every 2 h for 24 h on two different days (4 d apart), and the amount of melatonin (picograms per pineal) was determined. No sample was taken at 1130 on day 5. Error bars are ± standard error.

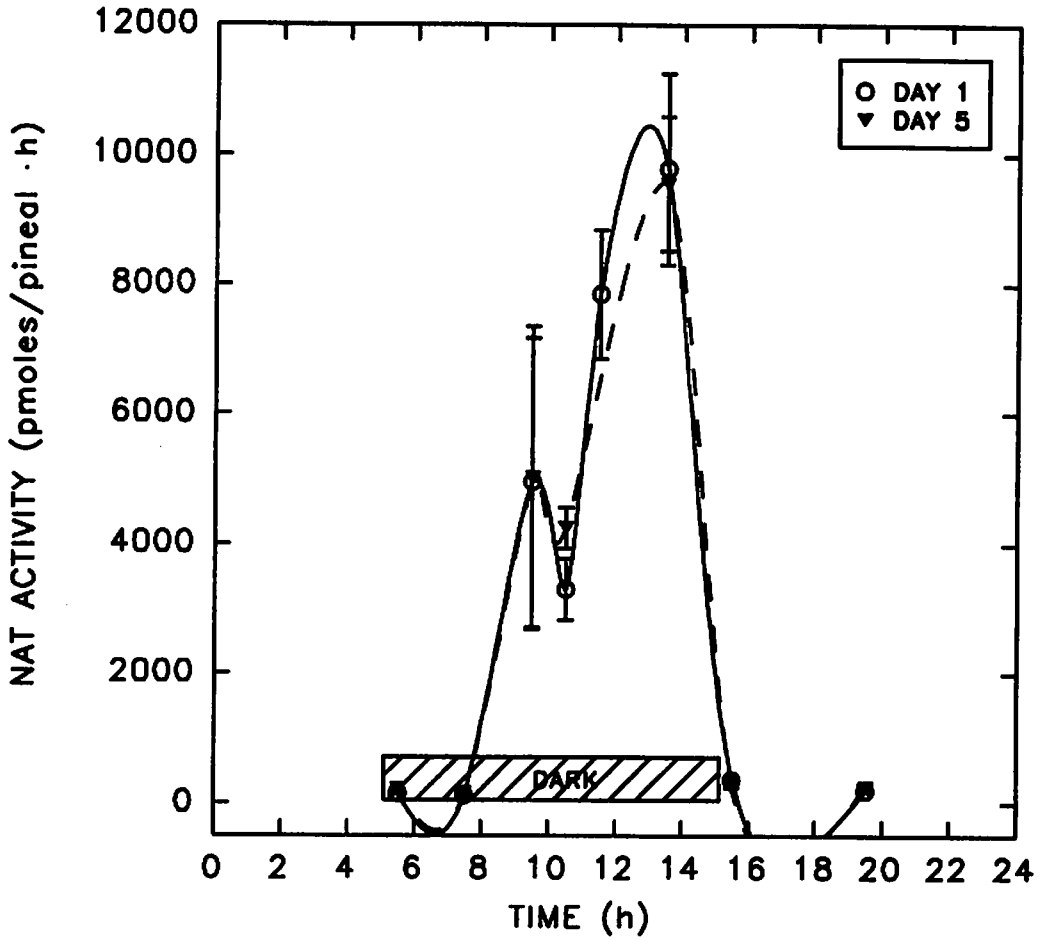


FIGURE 4-4. CIRCADIAN PINEAL NAT RHYTHM. After 2 weeks of LD 14:10 entrainment, rats (six per group) were sacrificed every 2 h for 24 h on two occasions 4 d apart, and the amount of NAT was determined (pmoles/pineal·h). Error bars are ± standard error.

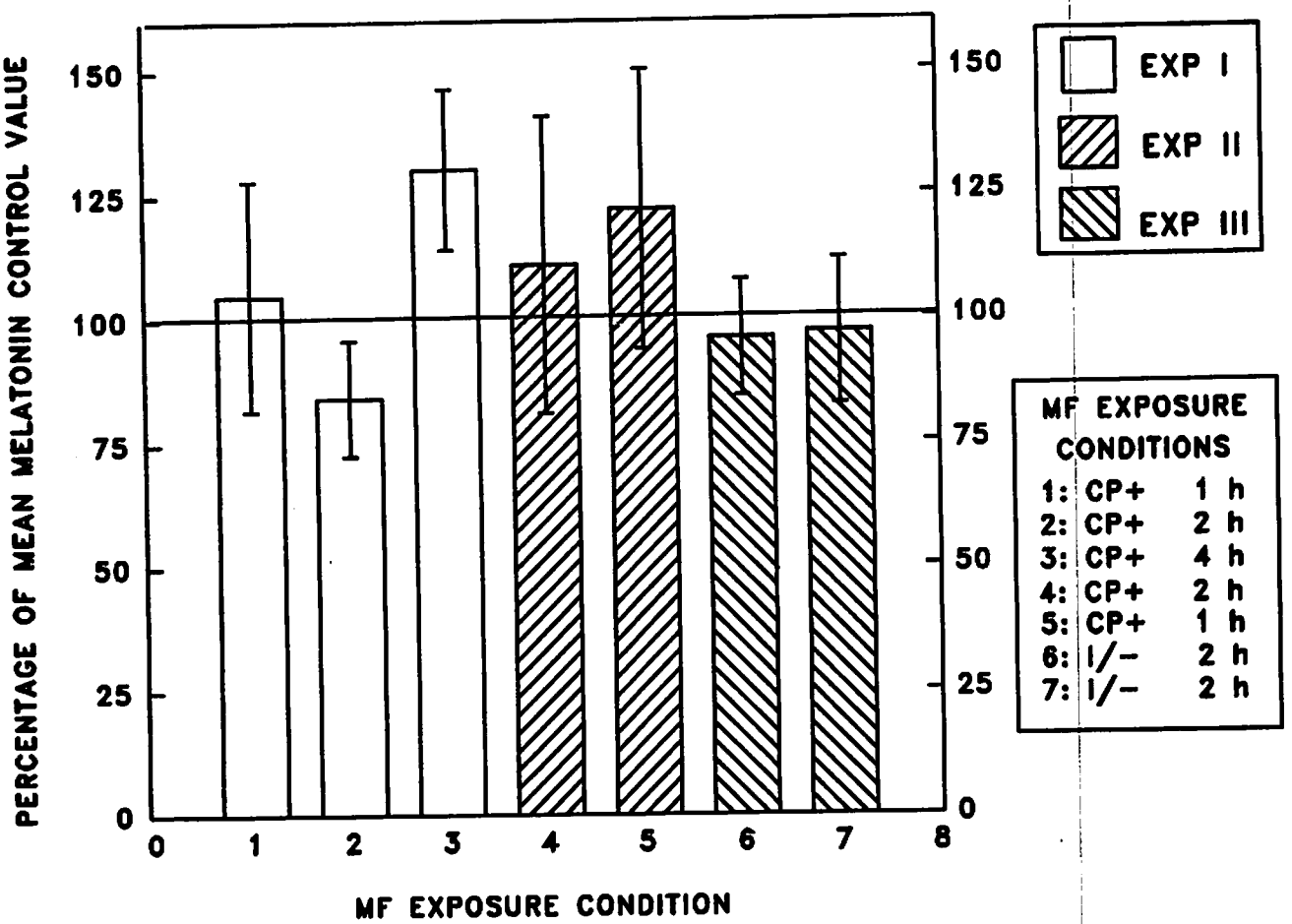


FIGURE 4-5. **PINEAL MELATONIN RESPONSE TO 1X TR-07 MF EXPOSURE.** During the nighttime (dark) peak in pineal melatonin, rats were subjected to TR-07 frequency and intensity EMF exposure in three separate experiments. The exposures in Experiment II were continuous, in the same direction as the ambient MF, and varied in length (1, 2, or 4 h). MF-exposures in Experiment III were a repeat of those in Experiment II. Exposures in Experiment IV were inverted to the ambient field, intermittent (45 s on/15 s off), and turned on rapidly to produce induced (eddy) currents. Immediately following exposure, exposed and unexposed animals (n = 6) were sacrificed, frozen (-60 °C), and later assayed for the amount of pineal melatonin per rat. The unexposed control group mean between MF exposure experiments differed in the absolute amount of melatonin per pineal, so the exposed melatonin/pineal response was calculated as percentage of control response within experiments (control = 100%). Bars are ± standard error.

4.2.3 Pineal Melatonin and NAT Response to maglev, DC, and AC MF Exposure

During this study, the control group means (6 animals per group) varied over a typical one-week series of MF exposures. ANOVA analysis followed by Tukey post hoc pairwise comparison showed that no controls were statistically significant from the mean of all controls or each other (e.g., Figure 4-6, "All CON"). The pineal melatonin level in unexposed controls (Figure 4-3) remained at maximum (about 2000 pg per pineal) for 4 h, from 4.5 to 8.5 h after the onset of the dark portion of the LD cycle, but the ability of specific MF exposures to influence the expected, control level of melatonin and NAT activity varied during this time.

Together, the results of three experiments (with animals exposed to MFs when melatonin reached maximum levels in the pineal considered as one group, 4.5−8.5 h after dark onset), showed that only inverted, intermittent DC exposures (net MF = −1.3 G, dB/dt = 267 G/s) produced a significant (46%) decrease in NAT ($p < .03$, Figure 4-6). The 1X, 7X, or 7X AC component intermittently exposed maglev MF animals did not differ in pineal NAT from unexposed controls sacrificed at the same time, and the apparent decreases in NAT levels in control 60 Hz and continuous maglev MF exposures (28% and 42%) were not statistically significant. During this same period of maximum melatonin in the pineal, none of the MF exposure conditions resulted in a significant change in pineal melatonin (Figure 4-7), although a 2-h continuous 7X maglev exposure depressed pineal melatonin 37%.

4.2.4 Pineal Melatonin

Pineal melatonin levels showed no statistically significant differences in response to maglev MF exposures at intensities lower than 7X TR-07 levels (1X, 2X, or 4X). At 1−4X MF intensities, no change from control-level melatonin was observed for exposure durations of 1, 2, or 4 h suggesting that there is no intensity or duration threshold within this range of MF exposure. The directionality (whether a field horizontal or parallel to the ambient field was used) also did not produce changes in pineal melatonin.

The timing of MF exposure during the dark phase greatly influenced the response of pineal melatonin. Two-hour intermittent exposures beginning 4 h after dark onset (0900−1100 hours) had no effect on melatonin under any exposure condition examined (Figure 4-8). A continuous 7X maglev exposure appeared to reduce melatonin 43%, but the variation of melatonin levels in individual animals was too great to demonstrate a statistical difference from controls.

Similarly, a 2-h continuous 7X MF exposure starting 3 h later (7 h after dark onset) depressed melatonin levels 33% below control levels (Figure 4-9). Exposure within this same time frame to a 7X AC maglev component depressed melatonin 41% ($p < .06$). All other MF exposures during this time period, at intensities up to 7X,

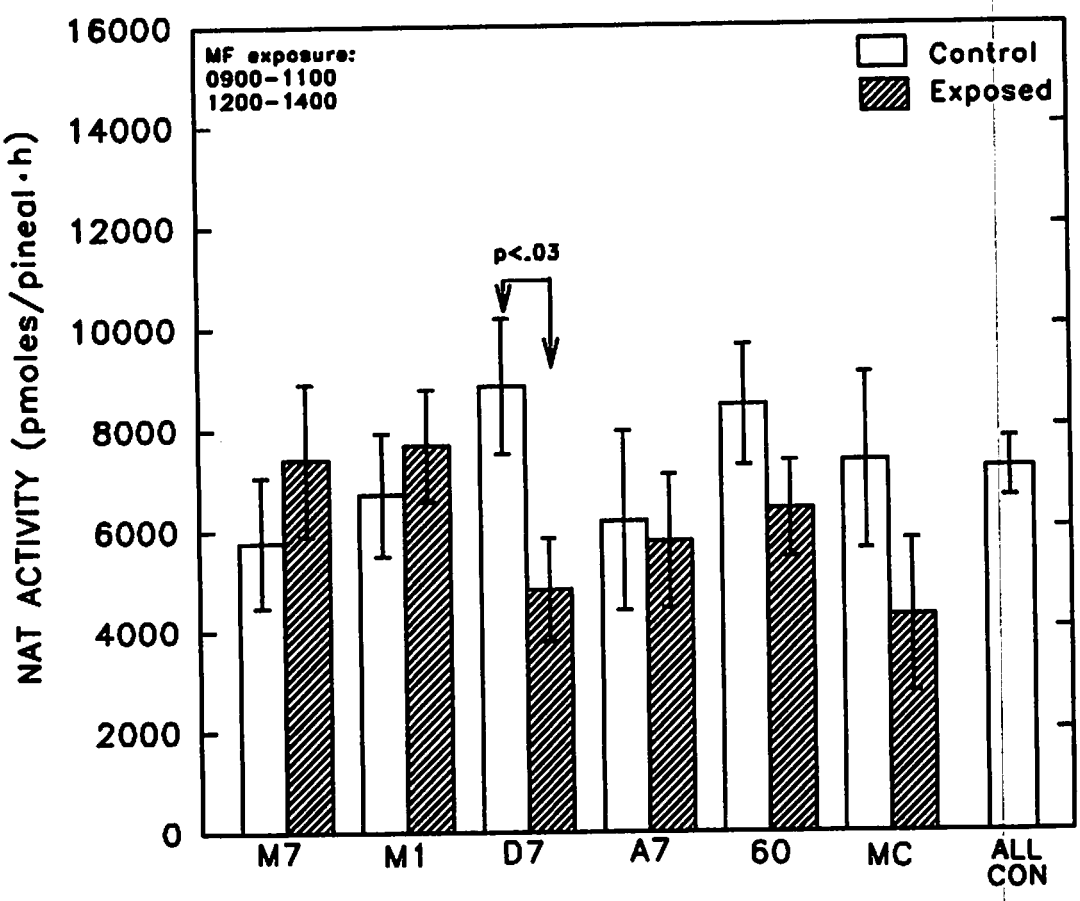


FIGURE 4-6. EARLY AND LATE MAGLEV MF EXPOSURE AND NAT RESPONSE. Animals (six per group) were entrained for two weeks (14:10 LD) and then exposed to various EMFs. Exposures were either at 0900-1100 or 1200-1400, and were combined (n = 12). Following exposure, the animals (and controls) were sacrificed and the pineals were removed, frozen (-60°C), and assayed for amount of pineal NAT per animal. Bars are ± standard error.

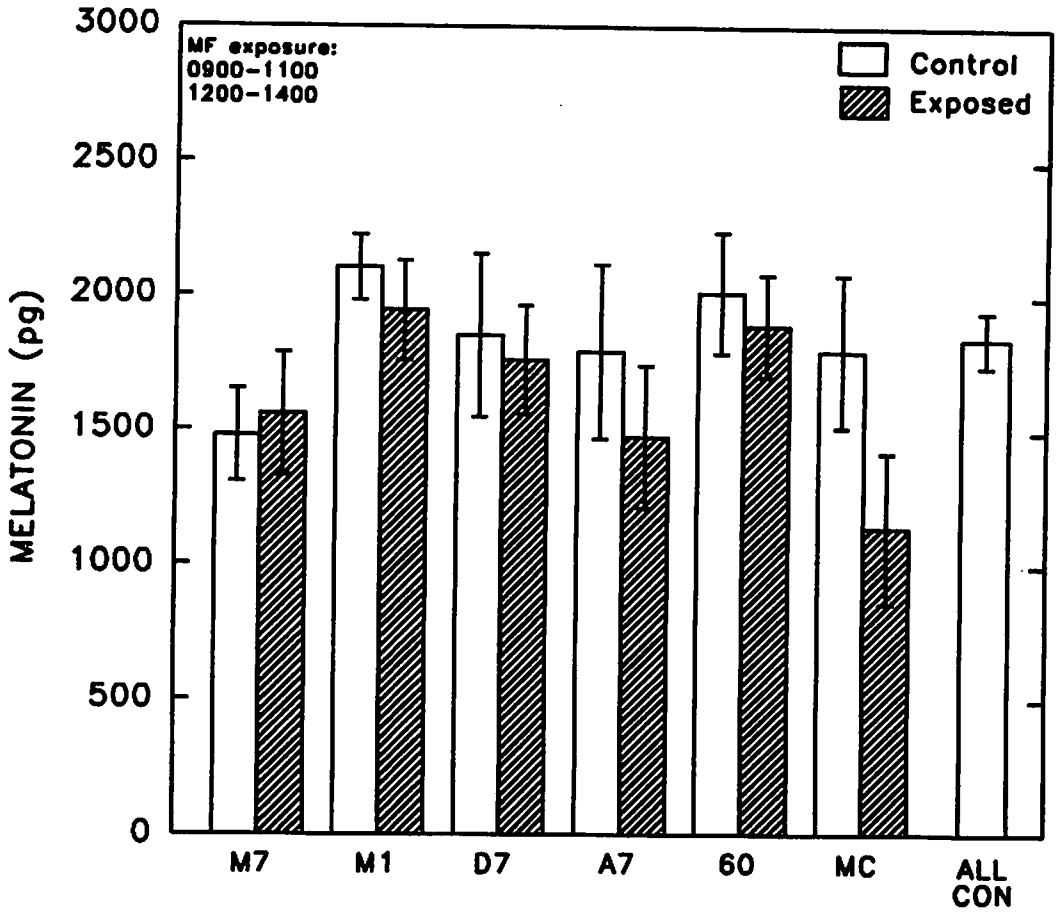


FIGURE 4-7. EARLY AND LATE MAGLEV MF EXPOSURE AND MELATONIN RESPONSE. Animals (six per group) were entrained for two weeks (14:10 LD) and then exposed to various EMFs. Exposures were either at 0900-1100 or 1200-1400, and were combined (n = 12). Following exposure, the animals (and controls) were sacrificed, and the pineals were removed, frozen (-60°C), and assayed for the amount of pineal melatonin per animal. Bars are ± standard error.

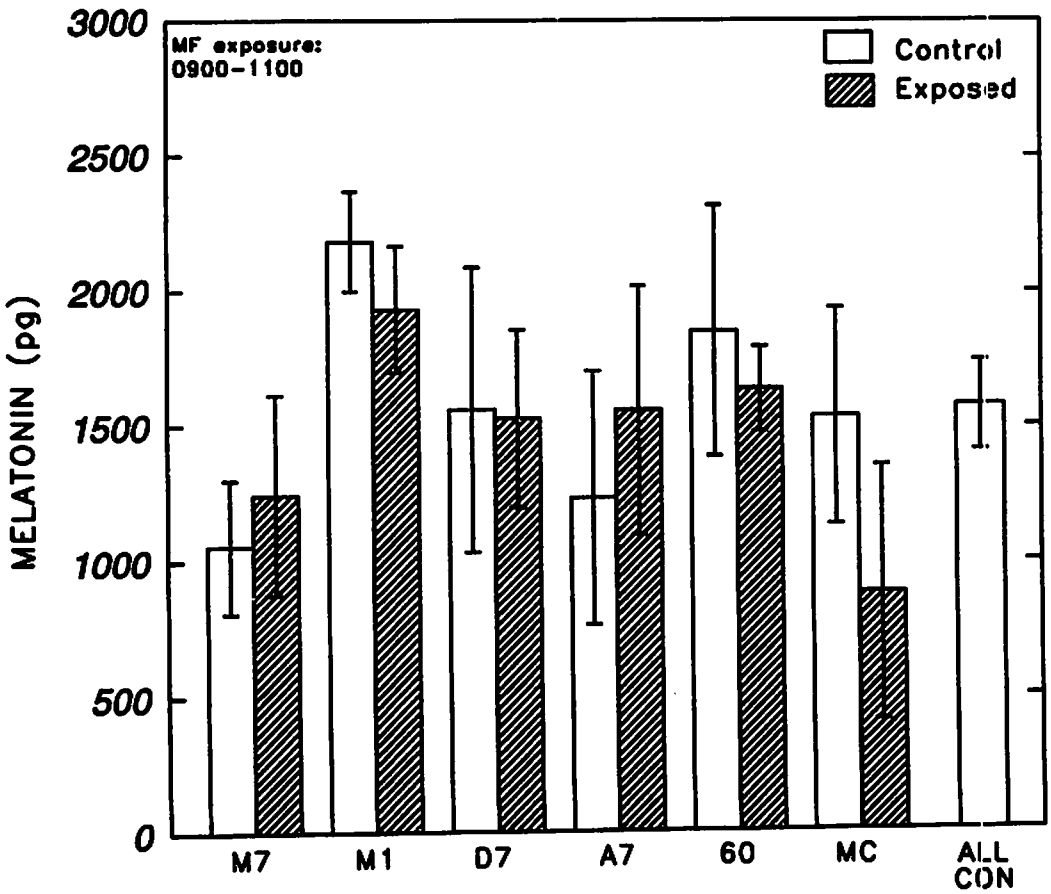


FIGURE 4-8. **EARLY MAGLEV MF EXPOSURE AND MELATONIN RESPONSE.** Animals (six per group) were entrained for two weeks (14:10 LD) and then exposed to various EMFs. Exposures were from 0900-1100. Following exposure, the animals (and controls) were sacrificed, and the pineals were removed, frozen (-60°C), and assayed for the amount of pineal melatonin per animal. Bars represent ± standard error.

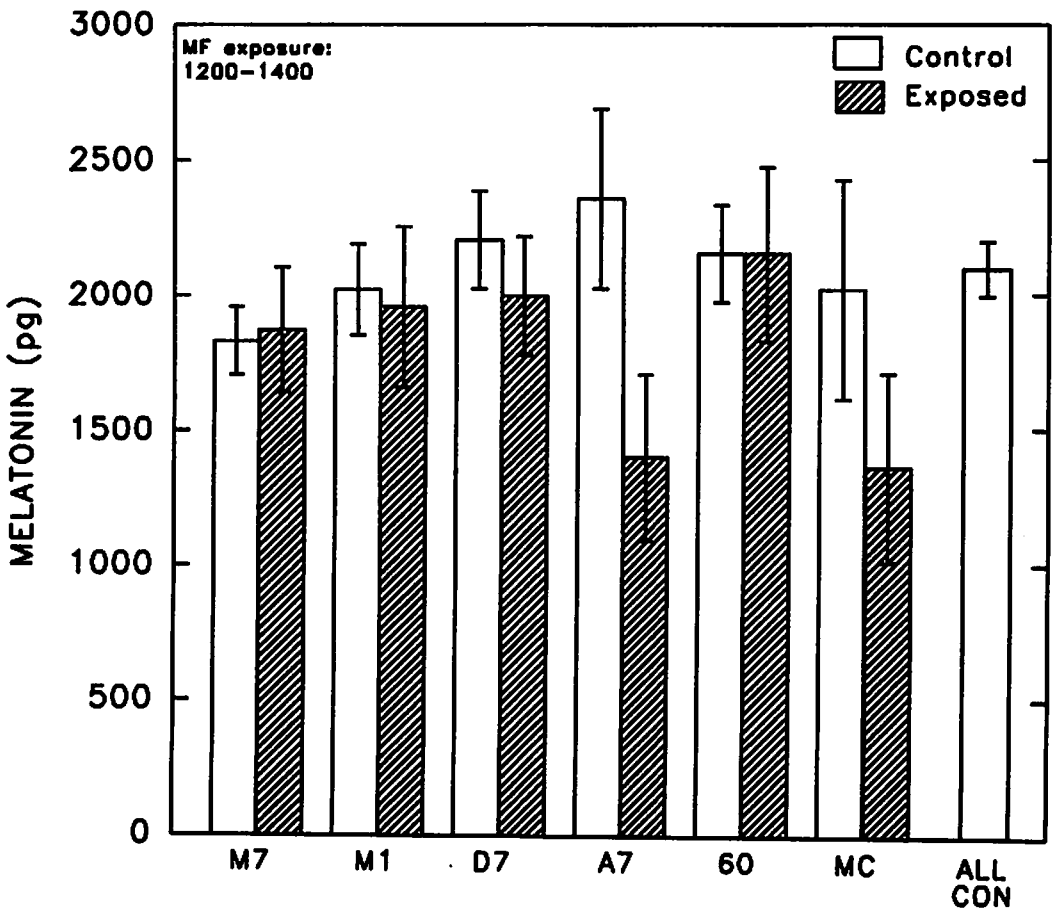


FIGURE 4-9. **LATE MAGLEV MF EXPOSURE AND MELATONIN RESPONSE.** Animals (six per group) were entrained for two weeks (14:10 LD) and then exposed to various EMFs. Exposures were from 1200-1400. Following exposure, the animals (and controls) were sacrificed, and the pineals were removed, frozen (-60°C), and assayed for the amount of pineal melatonin per animal. Bars represent ± standard error.

had no effect when compared to control animals. Average control group melatonin levels at this late stage of maximum pineal melatonin showed less variation than the average of individual control groups of 6 animals sacrificed with the "early" dark (0900–1100 hours) MF exposed groups (see Figure 4-8). The "late" group (1200–1400 hours) melatonin levels may have been stabilized by their longer length of time at maximum melatonin levels during dark (compared to those groups sacrificed at 1100), having been MF exposed during the first 2 h after melatonin levels reached maximum nighttime levels.

4.2.5 Pineal Serotonin-*N*-acetyltransferase

Pineal NAT was more responsive to MF exposure than was melatonin, both when MF exposure occurred during the first half (0900–1100 hours) and during the later half (1200–1400 hours) of maximum pineal NAT. The average control level of NAT in unexposed animals was 50% lower 4–6 h after dark onset (when the first peak of NAT activity was observed) than 7–9 h later during the time of maximum pineal NAT activity (4000 vs. 9500 pmoles/pineal·h) (Figures 4-10 and 4-11, respectively).

Two-hour inverted and intermittent DC exposures (net, −1.3 G) ending at 1100, during the time of the first pineal NAT activity peak (Figure 4-4) significantly decreased NAT ($p < .02$). As was the case with pineal melatonin levels, continuous 7X maglev exposure also decreased NAT levels by 47%. This decrease was not statistically significant, due to variation in sensitivity to MF exposure or the small number of animals (6) per group. An intermittent 60-Hz exposure (inverted, net −840 mG) also decreased NAT by a similar amount (48%).

An unexpected result of maglev exposure was seen when early (0900–1100 hours) 1X or 7X TR-07 exposures were intermittently given for 2 h. Typically, both light and EMF exposure decrease the dark peak in melatonin and NAT, but in both the 1X and 7X groups, pineal NAT increased 42%. However, t-tests did not statistically demonstrate a difference from control, unexposed animals.

Late-dark 2-h MF exposures, ending at 1400 hours, occurred during the time of maximum control pineal NAT activity (Figure 4-4). Control group NAT values were at least two fold greater than during the first peak in NAT (0900–1100 hours) and were more similar to each other in amount of NAT activity than individual control groups early in dark. Again, as with the combined dark MF exposures (0900–1100 and 1200–1400 hours), the individual 2-h (0900–1100 hours) 7X DC component TR-07 MF exposure showed a statistically significant decrease in NAT ($p < .02$). And again, a continuous 7X TR-07 maglev MF exposure also decreased NAT 40%, although this drop was not statistically significant.

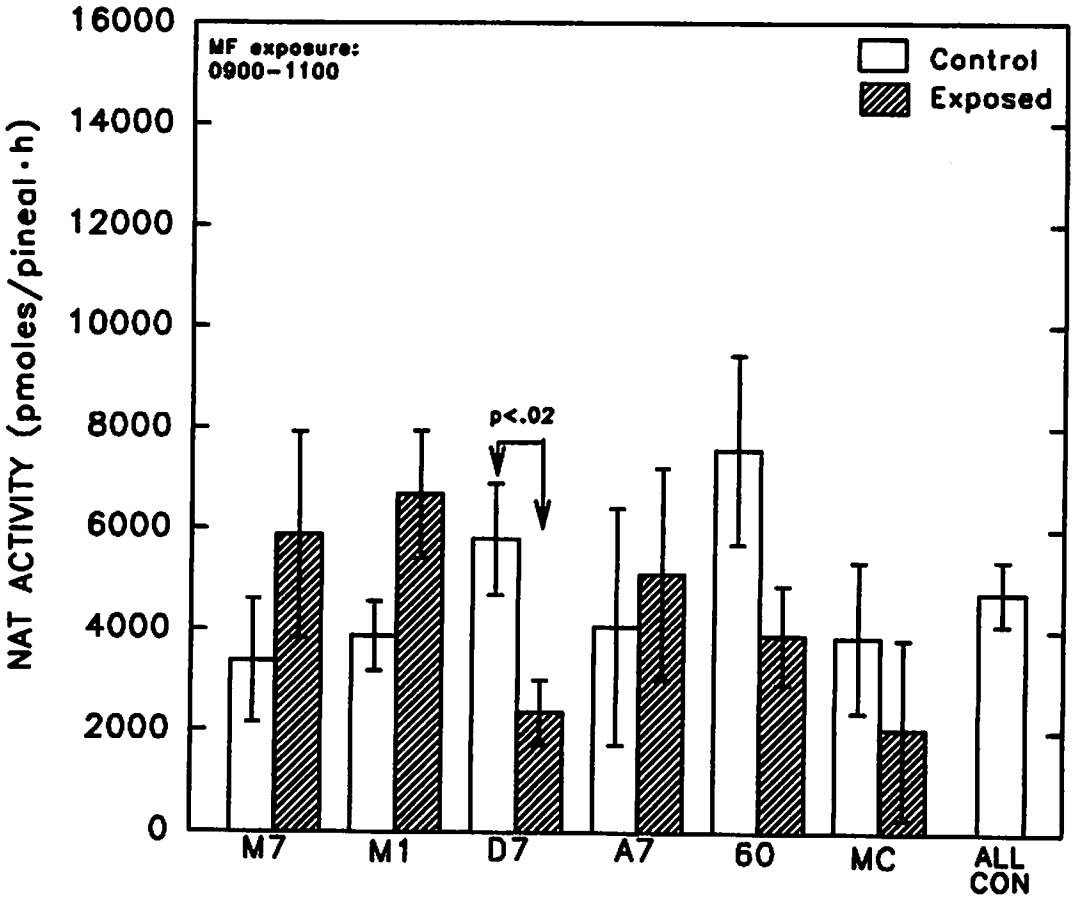


FIGURE 4-10. EARLY MAGLEV MF EXPOSURE AND NAT RESPONSE. Animals (Six per group) were entrained for two weeks (14:10 LD) and then exposed to various EMFs. Exposures were from 0900-1100. Following exposure, the animals (and controls) were sacrificed, and the pineals were removed, frozen (-60 °C), and assayed for the amount of pineal NAT per animal. Bars represent ± standard error.

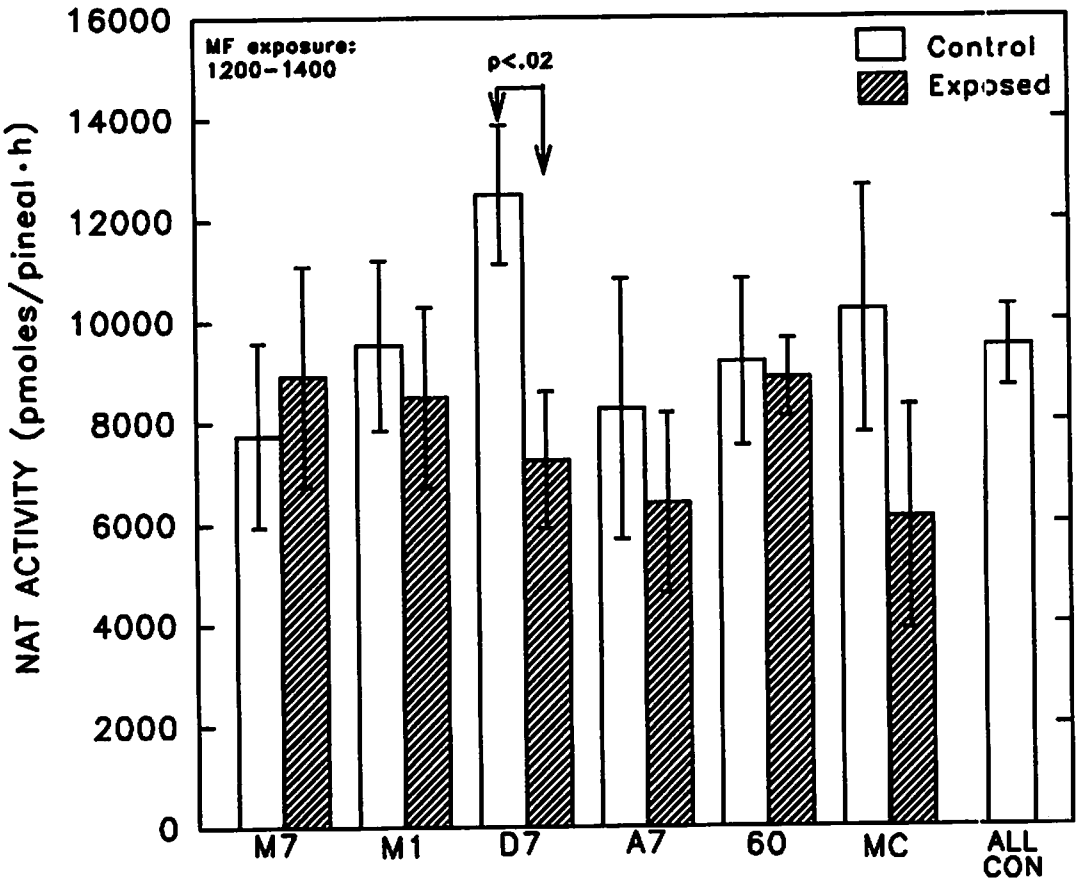


FIGURE 4-11. LATE MAGLEV MF EXPOSURE AND NAT RESPONSE. Animals (six per group) were entrained for two weeks (14:10 LD) and then exposed to various EMFs. Exposures were from 1200-1400. Following exposure, the animals (and controls) were sacrificed, and the pineals were removed, frozen (-60 °C), and assayed for the amount of pineal NAT per animal. Bars represent ± standard error.

5. DISCUSSION

5.1 TRANSPORTATION ELECTRO-TECHNOLOGIES AND THE EMF CONTROVERSY

This study demonstrates that certain components of simulated TR-07 maglev electromagnetic fields, and DC fields comparable to the geomagnetic field level, significantly depress pineal melatonin and NAT in rats. On the basis of available EMF information, maglev and other electric transportation systems should be considered as another one of many sources of electromagnetic field exposure in our environment which is capable of producing biological effects. Whether any of the EMF biological effects observed from power frequency sources (transmission or distribution lines), household, or occupational exposures pose a significant human health concern cannot be determined presently without an expansion of knowledge of actual and historical EMF exposure and a deeper understanding of the biological responses and the mechanisms that produce these changes.

The MF exposures in this study simulated, together and separately, both the DC and AC components of the German TransRapid TR-07 vehicle, as measured by Electric Research and Management, Inc. for the Federal Railroad Administration (FRA) in August 1990 [6 and 7]. The TR-07 is an electromagnetic attractive system, which continually adjusts the magnet current and its frequency to maintain proper levitation, guidance, and propulsion speed. The frequency of the EMF in TR-07 varies linearly with speed, up to about 300 Hz for 400 km/h. Other technologies, such as electrodynamic repulsive systems (EDS), provide constant current to superconducting magnets and would not be expected to produce an EMF spectrum as rich in AC or transient components as the TR-07. These could, however, result in substantially higher magnetic field levels in the vehicle.

The magnitude of the DC component also can be quite variable, depending on the speed of the vehicle and physical placement of the magnets in relation to areas of the vehicle expected to house passengers or railway workers. These factors, and the ability to shield magnetic fields to any level, if necessary, can limit any MF exposure to acceptable levels. So far, such levels have not been determined in the U.S. by the appropriate regulatory agencies (i.e., EPA, OSHA).

The introduction of maglev and other existing electric transportation technologies has raised an appropriate and as yet unanswered question in the current climate over their EMF health effects. Although there are few studies to date which document EMF levels produced by electrical transportation systems, this lack of information has been recognized, and the DOT/FRA has recently completed an extensive measurement and EMF characterization program.

Dietrich and Feero [6] and Dietrich et al. [7], in a two-volume report, measured the EMF fields produced by the German TransRapid TR-07 maglev vehicle, and subsequently surveyed conventional electric rail, the French TGV, and representative

urban transit systems. In a comprehensive series of measurements in the moving TR-07 vehicle that represents typical passenger operation, as well as EMF measurements along the right-of-way, in the station, on the platform, and at the electrical substation supplying power to the test facility, ERM documented an extremely complex pattern of time-varying, multifrequency EMFs. The DC fields in the passenger compartment ranged from 100−400 mG above ambient, with corresponding AC fields of 10−300 mG between 0 and 2000 Hz. Frequencies below 300 Hz were the greatest in intensity. The EMF frequency and intensity distribution varied with vehicle speed, guidance changes, and other support power demands, producing a very complex pattern of relatively low level exposure to passengers, quite comparable in intensity (but not in variability) to common environmental and home/office sources of EMF. The proposed Florida maglev trip will last 7 min one way, but shift workers could be exposed to up to 8 h/day. Therefore, the present experimental work examined both intermittent (occasional) and long duration EMF exposures.

Nakagawa and Koana [9] described and measured expected electromagnetic fields from the superconducting JNR EDS maglev vehicle that were greater than those in the TR-07 vehicle. The DC fields were 1−200 G and AC fields were 0.1−10 G. However, the Japanese EDS has been extensively redesigned to limit passenger exposure to less than 10 G in the cabin (greatest near the ends of the car and the floor), and shielding will be provided. Other electric railway transportation systems operated by the JNR also produced substantial EMF fields. Depending on the power source (ac, dc, or ac/dc), fields in train passenger compartments ranged from 500 mG to 40 G DC and 2 mG to 1.5 G ac.

Some United Kingdom electrified systems also produce substantial electromagnetic fields [36]. The DC fields measured on the London underground were reported at 2−20 G. This system is being switched to AC power, and test vehicles have produced 440 G DC fields at floor level, accompanied by large 100 Hz AC fields. Another British system, an AC overhead-powered train, produces 150 G DC fields at floor level. Intercity British Railway trains have been measured at 25 G at seat level, with 350 G fields at the floor.

From these studies it is clear that EMF exposures, like those that have reportedly produced biological changes here and in the literature, can occur while riding or working on electrified transportation systems. Whether these changes are related to adverse health effects, or are a normal adaptive, and transient response to our environment remains to be clarified by more detailed investigations. Since many people ride on these systems daily, such EMF exposures should be examined as thoroughly as 50−60 Hz (power frequency) exposures. Over the last 15−20 years, a substantial number of laboratory studies, especially those using animals, have described a broad range of biological effects caused by nonionizing electromagnetic fields [37]. Many of these studies have concentrated on the power frequency range [2], but it is clear that frequency, intensity, duration, and other physical aspects of the exposure, as well as individual and species-specific sensitivity, are significant factors in the biological responses that have been identified [38, 9, and 40].

5.2 EPIDEMIOLOGY STUDIES OF RAILROAD WORKERS

Only a few epidemiological studies have looked directly at the health of electrified-railroad workers, but, taken together, they have found no significant increase in risk over other categories of electrical workers exposed to electromagnetic fields. Lin et al. [41] included railroad workers in one of the occupationally EMF-exposed groups and found a doubling in the incidence of primary brain tumors (glioma and astrocytoma). Strong 50-Hz EMF exposures near interconnection and conversion rail substations (5 kV/m, 150 mG) did not cause changes in workers' EEG or hematology patterns, or increase general medical or psychological problems, which were carefully monitored in these workers [42]. Tynes and Anderson [43] found a doubling of male breast cancer risk in electrical workers, with the electrical transportation workers subgroup yielding a fourfold increase over the unexposed control group (four cases, one expected). Although suggestive of an increased risk, the confidence intervals (CI's) surrounding the cancer increase were large, and no single epidemiological study should be used as evidence to draw conclusions regarding the health effects of EMF exposure.

A Swiss study [44] showed a slight but significant increase in lymphoid cancer and leukemia in electric railway drivers when compared to metal construction and machine building workers. The measured EMF exposures in the driving compartment were on the order of 1.3 G for magnetic and 0.6 kV for electric fields, which is 2−3 orders of magnitude greater than typically reported for electric transmission line worker EMF exposure. However, this increased risk appeared after age 70 and was not believed to be significant by the authors. Wilkins and Hundley [45] examined the incidence of neuroblastoma in the children of electrical workers and found a general incidence increase (OR, odds ratio = 1.6), with the children of a railroad worker subgroup showing an OR of 1.9. Nakagawa et al. [46] found the incidence of cancer in railroad workers significantly below the national average in Japan, with no deaths from leukemia. However, no frequency data for EMF has been reported for any of these studies.

The epidemiology studies of electrical workers in the rail transportation industry suggest that the EMF level alone does increase cancer risk, but the level of confidence is low and the association is as weak as EMF cancer risk in other electrical occupations. More research is needed to improve our understanding of the relationship between cancer incidence and EMF exposure characteristics (frequency, duration, level of variability) in the workplace [47]. U.S. health studies on railroad workers exposed to diesel fumes found excess lung problems (i.e., emphysema, cancer).

5.3 CELLULAR DIFFERENTIATION RESPONSE TO EMF EXPOSURE

The results of this study suggest that maglev EMF exposure at up to seven times the intensity produced by the TR-07 vehicle (1.2 G DC + lower intensity AC frequency components) has no deleterious effect on the growth or differentiation of CEM T-lymphoblastoid cells. Since "windows" of both intensity and frequency have been

shown to be important in the biological response to MF exposures [11], the specific differences in MF exposure conditions in our experiments may not be optimal to elucidate a response in CEM T-lymphoblastoid cells similar to that seen by Lyle et al. [20].

Exposure to electromagnetic fields has been associated with carcinogenesis, especially with the promotional or co-promotional stages of carcinogenesis, but no cause-and-effect relationship has been established to date [2]. Carcinogenesis can be described as a process in which uncontrolled cellular replication and de-differentiation replaces normal growth and differentiation [48]. ELF fields have been shown to alter cellular replication [49]. Lyle et al. [50 and 20] have shown that T-lymphocytic cells are metabolically changed and their immune function decreased by exposure to ELF-modulated radio frequency (10 mW/cm^2, 450 MHz, 60 Hz sinusoidally amplitude-modulated, non-thermal microwave) and ELF (10 mV/cm, 60 Hz AC electric) fields.

These observations suggested that differentiation in the CEM T-lymphoblastoid cell line would be a sensitive indicator of MF exposure effects. The metabolic changes may be extremely exposure-specific, and the immunological changes observed by Lyle et al. [20 and 50] for CEM cells resulted from complex EMF exposures that were much higher than were used in the present study. This may be the reason that no responses were observed for CEM and the other cell lines under the exposure conditions used in this study. In spite of the present negative results, biological effects of maglev MF exposure on cell growth and cellular differentiation cannot be ruled out until additional exposure conditions (including "windows") are examined more carefully.

5.4 MELATONIN AND NAT RESPONSE TO EMF EXPOSURES

The only statistically significant ($p < .02$) pineal response to maglev-type MFs in this study occurred for intermittent DC magnetic fields at 7X TR-07 intensities and frequencies. NAT was significantly decreased (50−60% below control levels) by a 2-h 7X TR-07 DC exposure at 0900−1100 hours (at the time of the first NAT peak in activity) or at 1200−1400 hours (late dark). MFs of this strength have been measured, or are expected, for some superconducting-type maglev vehicles. MF fields simulating those that are produced by the TransRapid TR-07 vehicle had no statistically significant influence on pineal indoleamine rhythms.

The decrease in NAT due to MF exposure during dark replicated the results of Lerchl et al. [32 and 17], which showed that inverted, intermittent DC MF exposures as low as ambient for 1 h reduced NAT, suggesting that induced (eddy) currents could be responsible for decreasing NAT, the regulatory enzyme in the pineal serotonin to melatonin metabolic pathway. The length of the MF exposure may not be as important as the rate of MF onset in eliciting changes in pineal indoleamines.

However, in addition to the 7X DC MF exposure, a number of other exposure conditions (7X TR-07 AC frequency components and continuous 7X AC + DC TR-07 MF components together) did reduce melatonin and NAT as much as 50%, but the declines were not statistically significant. These responses may be considered as weak responses that could not be definitely established by the procedures used in this study, but represent MF-exposure conditions to be examined more carefully in further studies.

First, continuous 7X TR-07 maglev exposures decreased NAT by 40−47% (Figures 4-6, 4-10, and 4-11). Although this reduction was not statistically different from control NAT levels, it was as large as the depression seen using the DC MF exposure. Second, melatonin level was also decreased by 37% after continuous 7X maglev exposures (Figure 4-7) for combined dark exposures; when separated into early (0900−1100 hours) and late (1200−1400 hours) dark MF exposures, the depression of melatonin was 43% and 33% (but not statistically significant), respectively. Third, a 60 Hz, intermittent, power-frequency, 2 h exposure of 840 mG depressed melatonin by the same amount as continuous MF exposures (41%) when given in early dark (0900−1100 hours), but the reduction was not statistically significant. These MF exposures (continuous maglev and 60 Hz) consisted of AC components which would produce induced (eddy) currents in exposed animals (and cells) similar to the intermittent DC MF exposures that were found to significantly reduce pineal indoleamine metabolism (this study and Lerchl et al. [32 and 17]).

Although the percentage decreases in melatonin levels and NAT activity were in the range of 50%, small group sizes (n = 6), individual animal differences in entrainment and differences in sensitivity and response to MF exposure in both the control and exposed groups may have combined to dilute the group pineal melatonin and NAT differences between MF-exposed and control animals.

The amount of variation was the same within control and exposed animal groups. Individual animals vary in their entrainability to most endogenous and exogenous agents [51], and Rosenberg et al. [52] has shown that up to 20% of rats show no change in startle (perception and avoidance) to electric fields as great as 100 kV/m, as indicated by changes of activity. Small variations (minutes or fractions of an hour) in individual animal entrainment of pineal melatonin and NAT rhythms could have resulted in a large pineal melatonin and NAT response differences to MF exposure. Further attention to these specific elements should build on the results of this study.

Our data showed a difference in individual animal pineal melatonin and NAT levels in response to MF exposure, especially surrounding the transitions between light and dark levels of pineal indoleamines (4−6 h after dark onset). A small percentage of the animals could have lagged behind or been ahead of the group response at these transitions, which increased group variation in pineal melatonin and NAT. The discovery of two peaks in NAT during dark, with rapid changes in NAT activity, increased the likelihood that individual animals would have different levels of NAT (and melatonin) at any given time, and this was reflected in our results. This certainly could have contributed to the apparent increase (instead of the expected

decrease as a result of MF exposure) in NAT by early (0900−1100 hours) 1X and 7X maglev exposures.

The MF exposure times used in this study, in retrospect, were very near to these transitions. This, combined with individual variation of the animals, may have contributed to statistical differences within the control and MF-exposed groups. Now that these suspected complications have been identified, future studies can take advantage of this information. Increased group size (by increasing the number of animals per cage, using more cages, and replicating MF exposure for a given MF parameter) and optimal MF-exposure times (1100−1300 hours, more uniformly surrounding the center of the melatonin and NAT maxima during dark) would more rigorously test the ability of such weak, non-ionizing EMF field conditions to alter pineal rhythms.

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