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TRANSRAPID TR-07 MAGLEV-SPECTRUM MAGNETIC FIELD EFFECTS ON DAILY PINEAL INDOLEAMINE METABOLIC RHYTHMS IN RODENTS

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Abstract. This study examined the effects on pineal function of magnetic field (MF) exposures (ac and dc components) similar to those produced by the TransRapid TR-07 and other electromagnetic maglev systems (EMS). Rats (6/group.) were entrained to a 14:10 light-dark cycle and then exposed to a continuous, or to an inverted, intermittent (on = 45 s, off = 15 s, induced current = 267 G/s) simulated multifrequency ac (0-2 kHz) <u>and</u> dc magnetic field (MF) at 1 or 7 times the TR-07 maglev vehicle MF intensity for 2 hr. Other groups of rats were exposed to only the ac or the dc-component of the maglev MF. For comparison, one group was exposed to an inverted, intermittent 60-Hz MF. At the end of the exposure, each group was sacrificed and compared to an unexposed group of rats for changes in pineal melatonin and serotonin-*N*-acetyltransferase (NAT). MF exposures at an intensity equivalent to that produced by the TR-07 vehicle (1X; 0.1-50 mG, 1.6 kHz-10 Hz; 250 mG dc) had no effect on melatonin or NAT compared with sham-exposed animals under any of the conditions examined. However, 7X TR-07-level continuous 2-h MF exposures significantly depressed pineal NAT by 45% ($p < 0.03$) compared to controls. Pineal melatonin was also depressed 33-43% by a continuous 7X TR-07 MF exposure and 28% by an intermittent 60-Hz 850-mG MF, but the results were not statistically significant. This study demonstrates that intermittent, combined ac and dc MFs similar to those produced by the TR-07 EMS maglev vehicle alter the normal circadian rhythm of pineal indoleamine metabolism. The pineal regulatory enzyme NAT was more sensitive to MF exposure than melatonin and may be a more desirable measure of the biological effects of MF exposure.

INTRODUCTION

Maglev promises to be 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. The possibility of using magnetically levitated vehicles for high-speed ground transportation has been examined since the early 1970s. Germany and Japan have each spent in excess of one billion dollars to develop and test prototype maglev systems, the German TransRapid TR-07 maglev system using conventional magnet levitation and propulsion and the Japanese using superconducting magnets. The Japanese expect to demonstrate one of their designs by the mid-1990s, and final plans are underway to install a 22-km TR-07 maglev system in Orlando, Florida, in the same time frame. A National Maglev Initiative, led by the Federal Railroad Administration and supported by the Army Corps of Engineers and the Department of Energy, was established in 1990 by the federal government to explore the options available for using this technology in the United States.

In the last 25 years nonionizing electromagnetic field (emf) exposure has come under scrutiny as another potentially harmful environmental agent. Both electric and magnetic fields in the extremely low frequency range (3-3000 Hz), as well as static magnetic fields have produced biological effects in cellular and animal investigations.

Extensive animal studies have demonstrated the most significant and repeatable emf effects in the areas of emf perception, behavior, and neuroendocrine effects [2]. Wilson et al. [3] demonstrated depression of greater than 50% in the pineal melatonin rhythm in rats by continuous exposure to a 100-kV/m 60-Hz electric field for three weeks. However, the rhythm returned after the field exposure ceased. 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 serotonin-*N*-acetyltransferase (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 rhythm was also produced by the emf exposure [4].

Vasquez et al. [5] continued to add to the neuroendocrine effects observed as a result of emf exposure. Rats exposed to 39-kV/m, 60-Hz electric fields showed phase shifts of up to 4 h in the circadian rhythms of the neurotransmitters norepinephrine, dopamine, and the serotonin metabolite 5-hydroxyindoleacetic acid (HIAA) in the hypothalamus, striatum, and hippocampus.

Not only have environmental-level 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. [6, 7] showed that intermittent, 1-hour, earth-strength, dc MFs depress normal melatonin and NAT rhythms in the rat pineal. This suggests that transient fields that produce induced

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currents may contribute to biological response to emf exposure.

Electromagnetic fields produced by maglev and other electrified rail systems have not been well characterized, with the exception of a recent Federal Railway Administration (FRA)-sponsored study of the German TransRapid TR-07 maglev vehicle [8, 9]. Currently, the FRA is measuring the electric and magnetic fields produced by a number of electric-powered transportation systems, and detailed emf exposure information will soon be available.

From the information that is available 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 and depend upon the specific transportation system characteristics. In superconducting vehicles, dc fields could reach upwards of 150 G, with ac field magnitudes in the range of 1.0 G in the passenger compartment [10, 11]. In addition, it is likely that time-varying dc, power frequency (50-60 Hz), and transient ELF magnetic field components will be encountered.

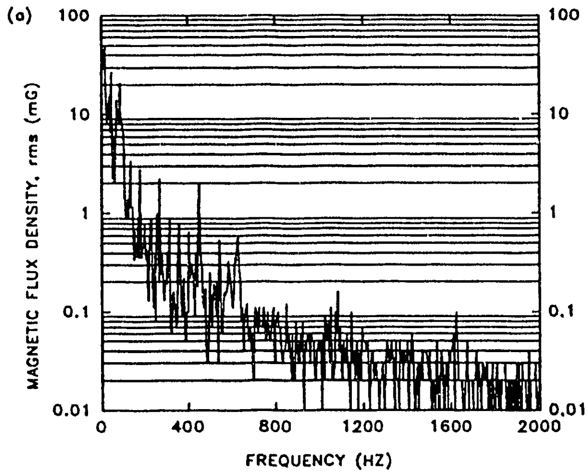
Which parts of this very complicated emf spectrum will prove to be most important in assessing the presence or absence of a potential health hazard is unclear at this time, but these transportation systems do have emf field emissions in the frequency and intensity ranges which have demonstrated to have biological effects in cell, animal, and human studies. No significant effects have been identified in the few studies that have examined transportation system passengers or workers for biological responses to emf exposure [10].

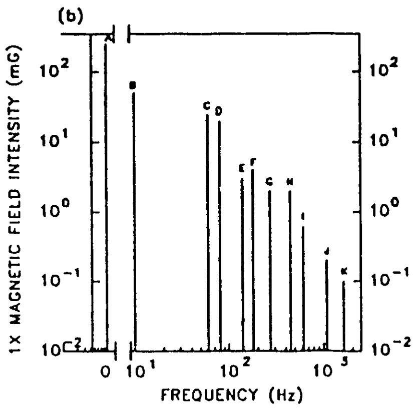
The purpose of this study was to begin examining the complex-spectra, time-varying emf fields produced by maglev transportation systems that use conventional EMS (TR-07) or superconducting magnet technology. Maglev MFs were simulated using the TransRapid TR-07 maglev spectra measured by Electric Research and Management, Inc. (ERM) [8, 9]. Using rats, MF exposures were used that are likely to be encountered by passengers and system workers, as well as MF conditions that have produced repeatable biological effects using power frequency or static dc fields.

MATERIALS AND METHODS

A pair of Helmholtz coils (r = 0.5 m) were oriented with the diameter perpendicular to the north-south ambient field. A bipolar power supply (Kepco, Flushing, NY, Model BOP 50-2M, 50 V, 0-2 A) was used to energize the Helmholtz coil system. The simulated maglev magnetic field (MF) (dc and multi frequency ac) spectrum was generated using a 286 AT 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 ramp rate of the signal can be varied over a wide range (microseconds to seconds) to vary dB/dt, producing an induced voltage in the Helmholtz coil and subsequent eddy currents.

Maglev magnetic field exposures were simulated from spectra collected inside the moving (168 km/h) passenger compartment of the TR-07 prototype vehicle, as measured by ERM in August 1990 [9]. Fig. 1 depicts the actual and simulated complex ac spectrum of this prototype maglev vehicle. The dc component of the TR-07 was 250 mG above ambient.





(c)

FREQUENCY (Hz)	INTENSITY (mG) 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

Fig 1. TR-07 Magnetic Field Spectrum. (a) Actual measurement recorded August 1990 by Electric Research and Management [9], at a velocity of 168 km/h. The dc component was 250 mG above the ambient field. Simulated TR-07 MF (b). The prominent frequencies (Hz) and their respective intensities, including a 250-mG dc component, were delivered simultaneously by computer to the Helmholtz coil. The entire spectrum was increased 7-fold for the 7X exposures (c).

Although the ac and dc MF intensities, and especially the transient profiles, are uniquely different, EMS maglev vehicles are expected to produce similar magnetic field profiles quite different from the dc, 60-Hz, and other magnetic field exposures that have previously been used in biological exposure experiments.

Male Sprague-Dawley (Cobb strain) rats (*Rattus norvegicus*), 44-47 d old, 100-120 g were entrained for two weeks to a 14:10 light-dark (LD) cycle (dark period [D] = 0500-1500), with dim red light present during the dark portion of the cycle. Food and water was available *ad libitum*. Conditions were constant at 22 °C and 50% RH. For every exposure group, six similarly treated animals served as controls.

Daily for 7 d, groups of six animals were placed into two cages that were modified with plastic barriers to allow individual containment and exposure of three rats per cage in the central area of the Helmholtz coils. MF exposures occurred during dark for 2 h, ending at 6 or 9 h after dark onset, when pineal melatonin and NAT are at maximum levels. Another group of six animals were exposed for similar lengths of time, ending 5 h after light onset (minimum melatonin and NAT).

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

1. Exposure length: 1, 2, or 4 h

2. Continuous MF exposure or intermittent exposures (repeating pattern of 45 s on, 15 s off) were quickly ramped, producing a dc-component-induced current of 37 (1X TR-07) or 267 (7X) G/s. Rapid application of an intermittent, inverted earth-strength static MF has been shown to significantly decrease pineal melatonin and NAT [6, 7].
3. Exposure to horizontal MF components or parallel to the inclination of the ambient magnetic fields (55°).

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

Immediately after an exposure, the exposed and control rats were alternately sacrificed, and the pineal was removed and frozen (-60 °C, dry ice, average time 30 s) until assay. Melatonin was determined by radioimmunoassay [7, 12], and serotonin-*N*-acetyltransferase activity (NAT; EC 2.3.1.5) was determined by radioenzymatic assay [13]. Differences between control and exposed groups of animals were compared using the Student t-test.

RESULTS

Simulated TR-07 MF 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 (Fig. 2). Continuous MF exposure during dark (maximum melatonin) for 1, 2, or 4 h in two

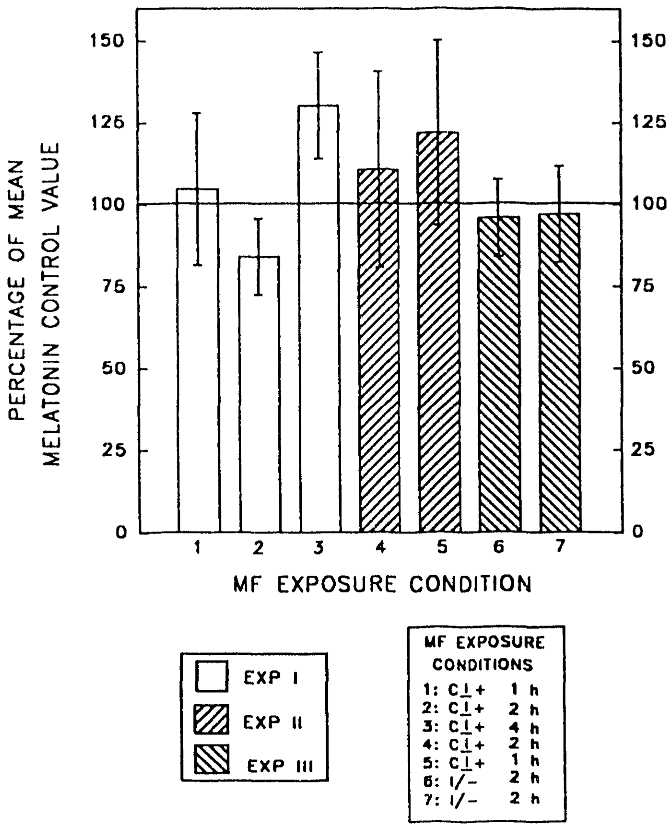


Fig 2. Pineal Melatonin Response to 1X TR-07 MF Exposure. During the nighttime (dark) peak in pineal melatonin, rats were subjected to TR-07 frequency and intensity MF exposure in three separate experiments. The exposures in Experiment I were continuous, in the same direction as the ambient MF, and varied in length (1, 2, or 4 h). MF-exposures in experiment II were a repeat of those in experiment I. Exposures in Experiment III were inverted to the ambient field, intermittent (45 s on/15 s off), and turned on rapidly to produce induced (eddy) currents. 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.

experiments 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.

TR-07 Maglev (7X) and AC- and DC-Component MF Exposures

Together, the results of three experiments (with all animals exposed to MFs when melatonin reached maximum levels in the pineal considered as one group, 4.5-8.5 hours after dark onset), showed that only 2-h inverted, intermittent 7X TR-07 dc exposures (net MF = -1.3 G, dB/dt= 267 G/s) produced a significant 46% decrease in NAT (Fig. 3,"D7", $p < .03$,). The animals exposed to the 1X, 7X, or 7X ac component intermittent maglev fields did not differ in pineal NAT from

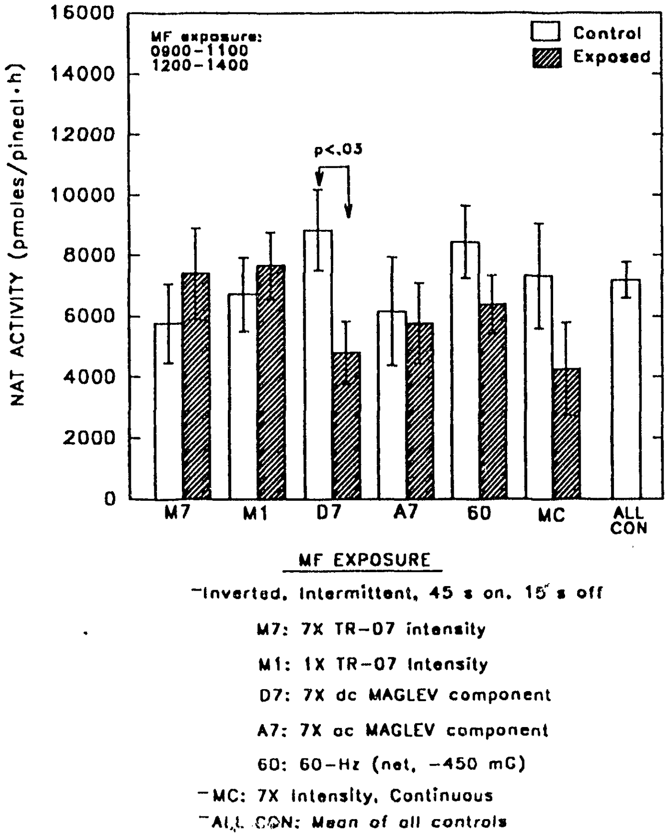


Fig 3. Nighttime MF Exposure and NAT Response. Animals (six per group) were entrained for two weeks (14:10 LD; D = 0500-1500) and then exposed to MFs. Exposures were either at 0900-1100 or 1200-1400, and were combined (n = 12). Following exposure, the animals (and controls) were sacrificed and the pineals were removed, frozen (-60 °C), and assayed for amount of pineal NAT per animal. Bars are standard error.

unexposed controls sacrificed at the same time, but 60-Hz and continuous maglev exposed NAT levels were decreased 28% and 42%, respectively, although these decreases 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 (Fig. 4), although a 2 h continuous 7X maglev

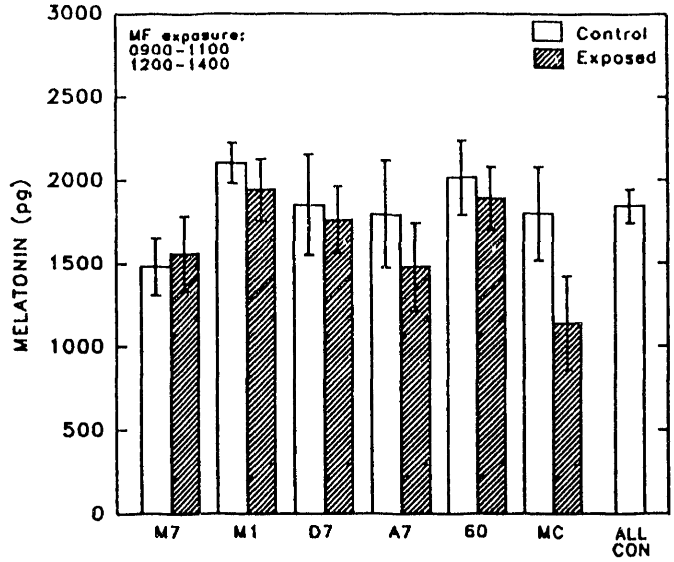


Fig 4. Nighttime MF Exposure and Melatonin Response. Animals (six per group) were entrained for two weeks (14:10 LD; D = 0500-1500), and then exposed to MFs. Exposures were either at 0900-1100 or 1200-1400, and were combined (n = 12). Following exposure, the animals (and controls) were sacrificed, and the pineals were removed, frozen (-60 °C), and assayed for the amount of pineal melatonin per animal. Bars are standard error.

exposure ("MC") depressed pineal melatonin 37%. The directionality (whether a MF horizontal to or parallel to the ambient field was used to expose groups of animals) also did not produce changes in pineal melatonin.

DISCUSSION

This study demonstrates that MF exposure at intensities produced by the German TransRapid maglev EMS vehicle does not produce changes (depression) in pineal melatonin and NAT levels, which have been used as a sensitive, reproducible, indicators of biological response to emf exposure [14-19]. However, when the dc component of the TR-07 MF was increased 7-fold (1-2 G), and delivered intermittently to produce induced eddy currents, pineal NAT was significantly reduced (50-60%) compared to control, unexposed animals ($p < 0.03$). MFs at this strength have been measured or are expected for EMS and EDS maglev vehicles.

In addition, a number of MF exposure conditions did reduce melatonin and NAT changes as much as 50%, but the declines were not statistically significant. Continuous 7X TR-07 maglev exposures decreased NAT 40-47% (Fig. 3). Melatonin was also decreased 37% by continuous 7X maglev exposures (Fig. 4). These MF exposures consisted of TR-07 ac MF components which would produce induced (eddy) currents similar to the intermittent dc MF exposures found to significantly reduce pineal indoleamine metabolism in this study and by Lerchl et al. [6,7].

Although the percentage decrease was large (in the range of 50%), small group sizes (n = 6), individual animal differences in entrainment, and individual sensitivity to MF exposure may have combined to dilute the group pineal melatonin and NAT differences between MF-exposed and control animals. The amount of group variation was large, and the same in both control and exposed animal groups.

Individual animals vary in their entrainability to most endogenous and exogenous agents [20], and Rosenberg et al. [21] has shown that up to 20% of rats show no change in perception of electric fields as great as 100 kV/m, measured by changes of activity, Variations in individual animal entrainment by as small as 1 h in pineal melatonin and NAT entrainment rhythms could have resulted in a large pineal melatonin and NAT group differences in response to MF exposure, as was seen in this study. Increased group size and optimal MF-exposure times identified in future studies will more successfully test the ability of these weak, non-ionizing MF exposure conditions to alter pineal rhythms.

Since melatonin has been shown to inhibit the growth of breast tumor cell lines *in vitro* [22], emf depression of pineal melatonin has been proposed as a possible mechanism to explain the growing human epidemiological evidence which suggests that emf exposure increases brain tumors and leukemia [4]. The plausibility of melatonin depression and the emf epidemiological link to cancer in humans has been strengthened by Wilson et al. [23], who, in a pilot study, found a decrease in the urinary melatonin metabolite 6-hydroxy melatonin sulfate (6-OHMS) at night in human subjects who used high-current electric blankets (relative to subjects using low-current electric blankets).

Whether decreased in pineal indoleamine metabolism does contribute to increases in carcinogenesis remains to be more solidly demonstrated, and any contributions from transportation system MF exposures will help to resolve this presently perplexing controversy.

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