Intern. J. Neuroscience, 113:1007–1019, 2003

ISSN: 0020-7454 / 1543-5245 online
DOI: 10.1080/00207450390220330

Taylor & Francis healthsciences

EFFECTS OF HIGH-FREQUENCY ELECTROMAGNETIC FIELDS ON HUMAN EEG: A BRAIN MAPPING STUDY

ALEXANDER V. KRAMARENKO

Central Clinic Hospital N5
Kharkov, Ukraine

UNER TAN

Cukurova University
Medical School
Department of Physiology
Adana, Turkey

Cell phones emitting pulsed high-frequency electromagnetic fields (EMF) may affect the human brain, but there are inconsistent results concerning their effects on electroencephalogram (EEG). We used a 16-channel telemetric electroencephalograph (ExpertTM®), to record EEG changes during exposure of human skull to EMF emitted by a mobile phone. Spatial distribution of EMF was especially concentrated around the ipsilateral eye adjacent to the basal surface of the brain. Traditional EEG was full of noises during operation of a cellular phone. Using a telemetric electroencephalograph (ExpertTM®) in awake subjects, all the noise was eliminated, and EEG showed interesting changes: after a period of 10–15 s there was no visible change, the spectrum median frequency increased in areas close to antenna; after 20–40 s, a slow-wave activity (2.5–6.0 Hz) appeared in the contralateral frontal and temporal areas. These slow waves lasting for about one second repeated every 15–-20 s at the same recording electrodes. After turning off the mobile phone, slow-wave activity progressively disappeared; local changes such as increased median frequency decreased and disappeared after 15–20 min. We observed similar changes in children, but the slow-

Received 7 December 2002.
Address correspondence to Prof. Dr. Uner Tan, Cukurova University, Medical School, Department of Physiology, Adana, Turkey. E-mail: unertan@cu.edu.tr

waves with higher amplitude appeared earlier in children (10–20 s) than adults, and their frequency was lower (1.0–2.5 Hz) with longer duration and shorter intervals. The results suggested that cellular phones may reversibly influence the human brain, inducing abnormal slow waves in EEG of awake persons.

Keywords brain, brain mapping, cellular phone, electromagnetic field

A cellular phone is a low-power, single-channel, two-way radio. Cell phone base stations are low-power multi-channel two-way radios. Therefore, base stations produce radio-frequency radiation, and they expose people near them to radio-frequency (RF) radiation. According to reports from the scientific community, the power from the mobile phone base station antennas is far too low to produce health hazards as long as people are kept away from direct access to the antennas. This nonionizing radiation is, however, fundamentally different from the ionizing radiation produced by x-ray machines. The effects of electromagnetic source to biological material depends on the frequency of the source (see Moulder & Foster, 1995). X-rays, RF radiation, and EMF from power lines are part of the electromagnetic spectrum, which are characterized by their frequency. Electric power in Turkey is at 50 Hz, and at 60 HZ in the US. FM radio has a frequency of around 100 MHz, microwave ovens have a frequency of 2450 MHz, X-rays have frequencies above one million GHz, and cellular phones operate at frequencies between about 800 and 2200 MHz. The electromagnetic particles of high-frequency X-rays have sufficient energy to break chemical bonds (ionization), which can damage the genetic material of cells leading to cancer or birth defects. Low frequency RE radiation is nonionizing. Therefore, there is no similarity between the biological effects of x-rays and RF radiation.

There was no convincing evidence that radio fields—in contrast to X- and Gamma-rays, ultraviolet and atomic radiation—can directly cause the changes in genes responsible for cancer development. Actually, most governments and cell-phone companies have claimed that the only possible biological effect of RF transmission is localized body heating. However, significant concern has been raised about possible health effects of RF electromagnetic fields. For instance, transgenic mice most susceptible to cancer demonstrated a 2-times increase in tumor rate (B-cell lymphomas) after exposure to microwaves at a power density roughly equal to a cell-phone transmitting for two half-hour periods each day, compared to control mice unexposed to RF fields (Repacholi et al., 1997). Children might develop cancer after exposure to the RF emissions from mobile telephone base stations in or near schools (see Repacholi, 1997).

The human body is an electrochemical instrument controlled by oscillatory electrical processes of various kinds; some endogenous biological electrical activities can be interfered via oscillatory aspects of the incoming radiation. Human in vivo studies indicated that the awaked EEC exposed to RF fields from a cell phone exerts a delayed increase in spectral power density, particularly in the alpha band (Reiser, Dimpfel, & Schober, 1995). Exposure to mobile phone radiation decreases the preparatory slow potentials in certain regions of the brain (Freude, Ullsperger, Eggert, & Ruppe, 1998) and affects memory tasks modulating the responses of EEG activity approximately 8 Hz specifically during cognitive process (Krause et al., 2000). There is a lot of evidence indicating nonthermal influences of RE fields in vivo, such as epileptiform activity in rats in conjunction with certain drugs (Sidorenko & Tsaryk, 1999), depression of chicken immune systems (Youbicier-Simo & Bastide, 1999), increase in chick embryo mortality(Youbicier-Simo & Bastide, 1999), increased permeability of blood-brain barrier in rats (Persson, Salford, Brun et al., 1997), and synergistic effect with certain psychoactive drugs (Lai, Horita, Chou, & Guy, 1987). These RF influences may induce many clinical signs and symptoms, such as headache, epileptic seizure, and sleep disturbance. The current scientific literature suggests that nonthermal RF field effects originating from cellular phones may have potential adverse health reactions, and this possibility should not be ignored even if only a small minority of people are at risk (because of inconsistent results).

Concerning the human brain, the above mentioned studies suggest that electromagnetic fields emitted by cellular phones may affect the human EEG. The current scientific literature is, however, full of inconsistencies. The aim of the present work was to reinvestigate the effects of the pulsed high frequency EMFs on human EEG in children and adults.

MATERIALS AND METHODS

Ten healthy young males and 10 children (12 years old) voluntarily participated in the study. The subjects were healthy and free of neurological and psychological signs and symptoms. During sessions, the subjects were sitting on an arm chair within a sound-isolated room. Sixteen electrodes were placed over the scalp according to the international 10–20 system, to record EEG. The reference was the sum of all the electrodes (common reference). The subjects were awake and their eyes were open during recordings, which were made using a 16-channel telemetric electroencephalograph made by one of us (AVK) (ExpertTM, Kharkov, Ukraine). This device uses digital telemetry and allows recording for a long time up to 24 h. EEG signals are transmitted digitally to the registration device via radio frequencies. The wireless system significantly simplifies the EEG examinations during research and clinical use. It is much less sensitive to the pulse and systematic noise than any other stationary EEGs. The built-in processor allows us to carry out digitization, filtration, compression, and coding of the signal directly in the EEG-amplifier. This allows us to transmit digital EEGs wirelessly with no interferences, including 50 Hz background noise. The high input resistance allows using the standard EEG gel for 24-hour EEG recording, reducing many physiological artifacts. EEG was subjected to spectral analysis including multiple mapping of amplitude characteristics and spectra of selected ranges. 3-D reconstruction of the functional focus was possible with availability of arbitrary or MRI-compatible shear planes.

EEG recordings were made in awake subjects before and during a call with a usual radiophone and a cellular phone. The carrier frequency of our cell phone was 900 MHz with a frame-frequency of 217 Hz. So, the usual radiophones provide continuous radiation usually up to 100 MHz with an emitted power up to 3 mW, whereas cell phones transmit the information in frames (217 Hz), the transmitter works with zero power between frames. In the on mode, the cell phone emits 3–4 W in immediate vicinity of the active ear and brain structures. The effects of EMF emitted by cell phones is an inverse proportion to squared distance. For instance, let us suppose that the field strength is X during calling (phone is near ear, distance = 1 cm); if we increase the distance to 10 cm, the field strength decreases to X/100. When a person lives near a cellular station (10 W, distance = 50 m), the field strength decreases to $(50/0.01)^2$ = 25000000 times. This is why the experiments cannot find any signs of EEG changes when the transmitter is placed far from the skull (40 cm or more) as reported by some investigators.

RESULTS

In order to understand the flow of current in a conducting medium like the human brain, the isotonic NaCl solution was put in a container and the antenna of a cellular phone was placed four cm apart from this container. The current flowing in this conducting medium could be registered using the weakly polarized Ag-AgCl EEG-electrodes in a low-frequency oscillograph (see Figure 1). This experiment suggests that potentials of several or tens of milivolts with

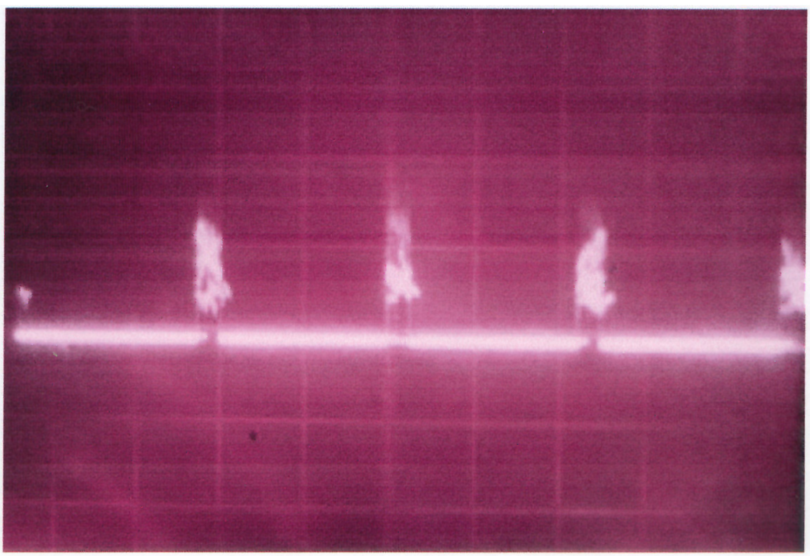

FIGURE 1. A snapshot from an oscilloscope: pulses emitted by a cellular phone recorded from an isotonic NaCl solution using Ag-AgCl EEG electrodes. Each square shows the voltage (vertical line = 2 mV) and time (horizontal line = 2 msec). Ericsson A1018S 900 MHz phone. (See Color Plate II at end of issue.)

a pulse frequency of 217 Hz may occur within the brain structures while using a cellular phone.

Figure 2 illustrates the map of the EMF generated by the cellular phone. Notice the highly complicated spatial distribution of the signal, and its locking in the mediums with maximum conduction. That is, the largest physiological effects will be strongly pronounced in places with largest area of contact with liquid. The locking of the EMF through the area of ipsilateral eyeball suggests that the influence on the basal surface of the brain might be stronger than the areas directly adjoining the antenna. All areas with intensive liquor dynamics become—according to Figure 2—the places with possible local gradients. The changes in EEG will be interesting during the presence of the EMF emitted by a cell phone. This is, however, a difficult engineering task. The traditional electroencephalogaphs cannot properly function because of too much noise, and the signal filtration is not a successful method suitable for elimination of noise induced by EMFs from cell phones. Nevertheless, the telemetric-

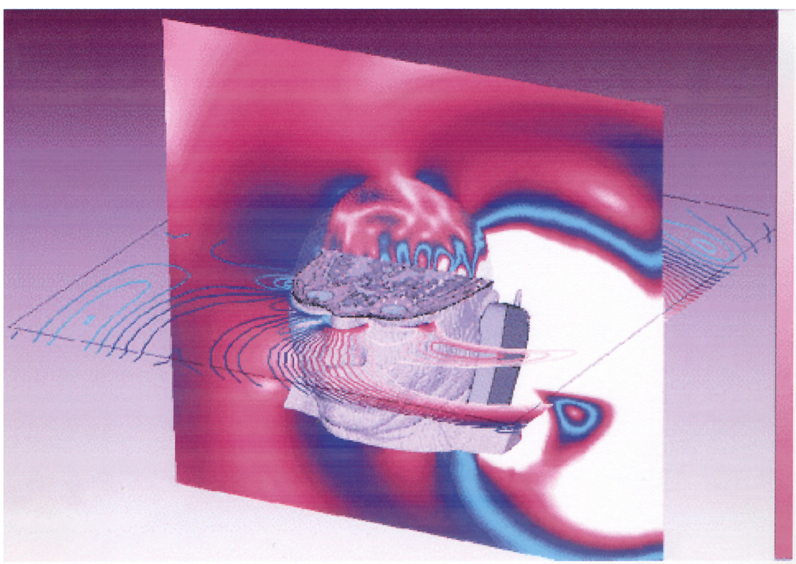

FIGURE 2. The map of the EMFS generated by a cellular phone, synthesized by "CST Microwave studio" program (published by authority of "Electron Trade" company, Russia). (See Color Plate III at end of issue.)

digital system used in this study allowed us to record the EEG signals without interference. Initially, these EMFs cause alpha depression; the frequency of the main EEG rhythm retains a high precision, and the signal spectrum changes slightly. If the single EEG channels were separately analyzed, there is some reliable increase in the median frequency of spectrum; occasionally, single sharp waves were also recorded in the areas close to antenna. Most of these changes were previously reported (see Lebedeva et al., 2000). Figure 3 illustrates the raw EEG without using our telemetric system (top: A) and after using our telemetric system (bottom: B). As seen in Figure 3B, we could record EEG during cell phone emitting (on) without noise.

Interestingly, the periodical slow wave activities were also observed in EEG after turning on the cell phone. Actually, there were no visible changes in EEG for 10–15 s following turning on the cell phone (see Figure 3B). After this period, the spectrum for the median frequency increased in areas close to the antenna. Following this period (i.e., within 20–40 s) a slow-wave activity appeared in the same areas; as the slow waves appeared, the median frequency decreased. The slow-wave activity lasted for about 1 s and then abruptly disappeared. The slow-wave activity exhibiting antiphase was sometimes observed in the areas contralateral to the antenna of the cell phone. Figure 4 illustrates the slow-wave activity in E7, F8, and T3 leads (left side); the picture on the right side of Figure 4 shows the enlarged part of the slow waves with brain mapping. Interestingly, the frontal areas are activated bilaterally, but the temporal areas are activated contralaterally (red areas: slow waves). Maximum power spectral density of these waves were within the range of 2.5–6.0 Hz, at the leads of maximum EMF strength. After the period of slow-wave activity, the median frequency slightly increases and apparently normal EEG was recorded. However, the slow-wave activity repeated periodically at the same leads every 15–20 s.

Figure 5 illustrates the mapping of the slow-wave activity in relation to the high frequency EME emitted by the cell phone. As seen in Figure 5 (right side, three dimensional pictures), the maximum slow-wave activity (above: red area) coincides with the maximum field strength. On the left side, the location of the slow-wave

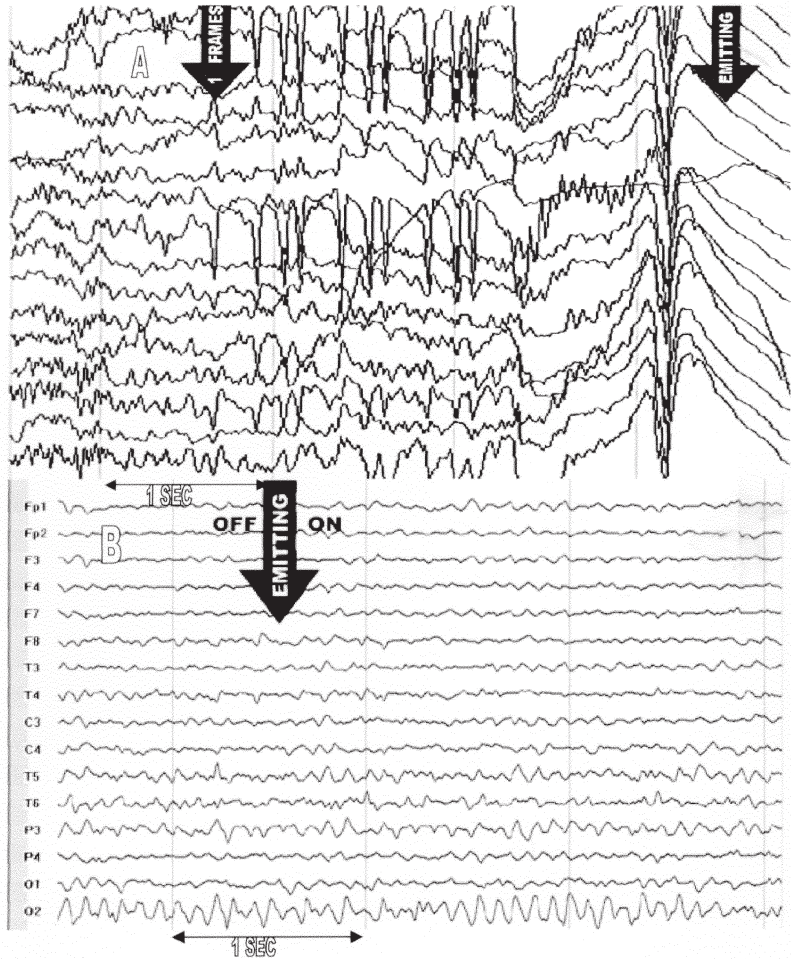

FIGURE 3. EEG in an awake subject before and after turning on the cell phone (*arrows*). Notice the noise in the raw EEG depicted above (A). Below (B), the EEG before and after (off, on) turning on the cellular phone. Notice the noise-free recording during using the telemetric registration system (ExpertTM EEG system, TREDEX Company Ltd., Kharkov, Ukraine).

activity is visualized. Five brain slices (see the skull) are illustrated consequently, red areas being the most pronounced slow wave activities in EEG. The red areas show that the EEG changes occur at the basal regions of the brain. Here, we discovered a total correspondence of both images (slow waves and EMFs), even taking into

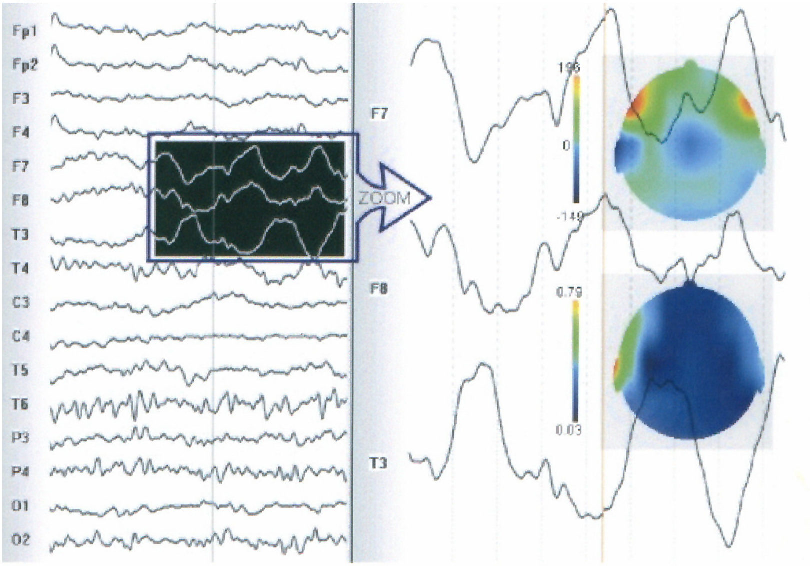

FIGURE 4. Slow-wave activity recorded at F7, F8, and T3 leads (*left*); its amplitude and frequency distribution are shown on the right. Eyes open, awake subject. (See Color Plate IV at end of issue.)

consideration the contralateral areas. The effects of the EMFs emitted by the cell phone was reversible. That is, the slow waves progressively disappeared in ten minutes after turning off the cellular phone.

The effects of EMFs on EEG were more pronounced in children (12 years old). That is, the slow-wave activity appeared earlier (approximately 10–15 s after turning on the cell phone) with higher amplitudes, lasted longer (2–3 s), their frequency was lower (1.0–2.5 Hz), and they occurred more frequently.

DISCUSSION

There was no visible change in human EEG after turning on the cell phone, except an increase in the median frequency detected only following spectral analysis. However, after a latent period lasting for about 15–20 s in adults and 10–15 s in children, a short-lasting

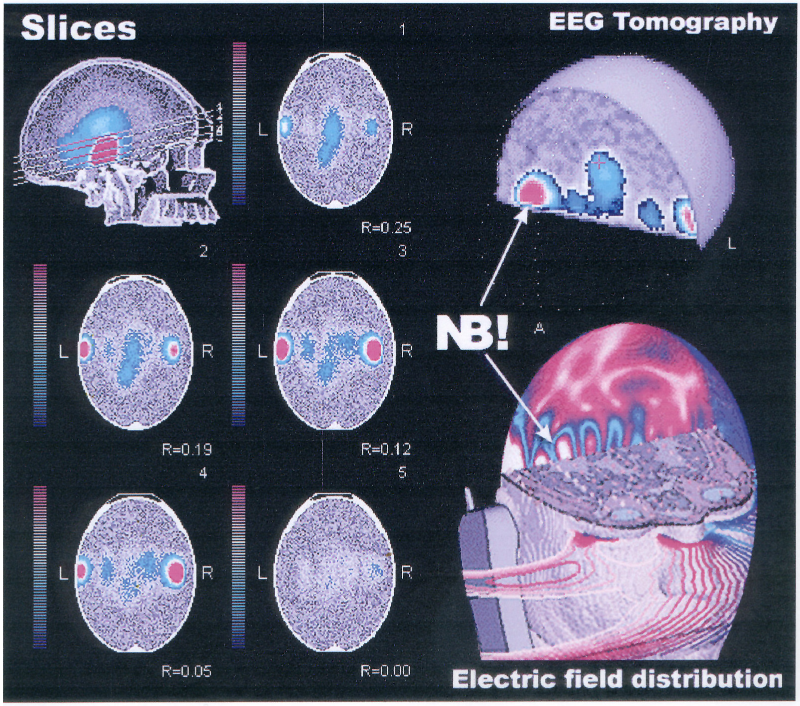

FIGURE 5. Comparison of probabilistic EEG tomography with the map of a cellular phone's EMFs. Pictures are from "Electroencephalograph ExpertTM system" (Tredex Company, Kharkov, Ukraine). (See Color Plate V at end of issue.)

slow slow-wave activity appeared in EEG. The spectral analysis indicated that the frequency of the slow waves ranged from 2.5 to 6.0 Hz in adults and from 1.0 to 2.5 Hz in children. Thus, the periodic delta and theta waves appeared in adults, and only the delta waves appeared in children.

The results of the present work clearly showed that the EMFs emitted by a cell phone affected the human EEG. It is indeed expected that EMFs in brain leading to afferent electrical signals may cause subsequent processing events in the brain, like other stimuli (Marino, 1993; Marino et al., 1996). However, the periodically occurring slow waves are obviously abnormal for a healthy human subject, since there are no delta waves in EEG of awake persons. Interestingly, the slow-wave activity did not disappear even if the cell phone was turned off; the slow waves progressively decreased in amplitude and then disappeared within tens of mins. There are some animal studies supporting these results. For instance, acute exposure of rats and rabbits to continuous microwaves increased EEG delta activity (Shandala et al., 1979). Similarly, Takashima et al. (1979) have reported a decrease in the high frequency EEG bands and an increase in the low frequency EEG bands. On the other hand, no uniform changes in EEG power spectra were also reported following exposure to continuous microwaves (Mitchell et al., 1989).

Increase in delta power was frequently reported following exposure to EMFs in animals (see Hermann & Hossmann, 1997). This was usually attributed to the thermal effects of EMFs in the brain: the increase in slow wave activity following exposure to EMFs may reflect the thermoregulatory response of the brain through the hypothalamus. The thermoregulatory effect may indeed play a role in the appearance of the slow-wave activity in the EEG. This is, however, unlikely for our study, since the delta waves occurred after a latent period of 15–20 s, lasted only for a few seconds, and occurred periodically every 15–20 s; they were not continuous. Moreover, the rise in brain temperature does not exceed 0.01–0.1ºC during exposure to EMFs emitted by cell phones, if blood flow and conduction is taken into account (Riu & Foster, 1999). Furthermore, the periodically occurring slow wave activity usually recorded at the contralateral leads to the antenna of the cellular phone, and coincided with the strongest EMFs.

There are inconsistent results in the scientific literature concerning the influence of EMFs emitted by cell phones on the human EEG. Our results clearly indicate that the cell phones may directly influence the human brain. This may be a direct influence of the EMFs on nervous system, since the EMFs were shown to induce afferent electrical signals like other stimuli within the human brain (see Marino et al., 1996). Consistent with our results, it was found previously that the brain electrical activity changes during exposure to EMFs (Bell et al., 1992; Lebedeva et al., 2000; Reiser et al., 1995); inconsistent with our results, it was reported that EEG was not affected by active cell phones (Hietanen et al., 2000; Roschke & Mann, 1997). Recently, Croft et al. (2002) have reported that exposure to acute mobile phone operation altered the resting EEG, decreasing 1–4 Hz activity, and increasing the 8–12 Hz activity and the midline frontal and lateral posterior responses in the 30–45 Hz band. These authors found alterations in awake EEG, but did not find any increase in delta wave activity, contrary to our results. Croft et al. (2002) discussed the possible origins of the inconsistent results on the effects of mobile phones on the human brain. It is indeed possible that sitting on a chair for a long time would cause drowsiness in the subjects, but we required the subjects to keep their eyes open and keep awake during EEG recordings.

CONCLUSION

We studied the effects of the EMFs emitted by cellular phones on the human EEG in adults and children. The EEG was found to show normal activity during exposure, except a slight increase in the global median frequency. However, a short-lasting slow-wave activity occurred after a latent period of 15–20 s after turning on the phone. We observed these slow-waves, within the delta range, periodically in every 15–20 s. After turning off the phone, they progressively decreased in amplitude and disappeared in ten of mins. We have concluded that the EMFs emitted by cell phones may be harmful for the human brain, since the delta waves are pathological if seen in awake subjects. On the other hand, the slow wave activity was more pronounced in children than adults, indicating that the children may be more vulnerable to the adverse health effects of mobile phones than adults, probably because absorption of microwaves is greatest in an object about the size of a child's head (Gandhi et al., 1996); the radiation can penetrate the thinner skull of an infant with greater ease. We are seriously concerned about possible risks to human brain from cell phones.

REFERENCES

Bell, G. B., Marino, A. A., & Chesson, A. L. (1992). Alterations in brain electrical activity caused by magnetic fields: Detecting the detection process. *Electroencephalography and Clinical Neurophysiology, 83*, 359–397.

Croft, R. J., Chandler, J. S., Burgess, A. P., Barry, R. J., Williams, J. D., & Clarke, A. R.

(2002). Acute mobile phone operation affects neural function in humans. *Clinical Neurophysiology*, *113,* 1623–1632.

Freude, G., Ullsperger, P., Eggert, S., & Ruppe, I. (1998). Effects of microwaves emitted by cellular phones on human slow brain potentials. *Bioelectromagnetics, 19*, 384–387.

Hietanen, M., Kovala, T., & Hamalainen, A. M. (2000). Human brain activity during exposure to radiofrequency fields by cellular phones. *Scandinavian Journal of Work and Environmental Health, 26*, 87–92.

Hermann, D. M., & Hossmann, K.-A. (1997). Neurological effects of microwave exposure related to mobile communication. *Journal of Neurological Sciences, 152*, 1–14.

Krause, C. M., Sillanmaki, L., Koivisto, M., Haggqvist, A., et al. (2000). Effects of electromagnetic fields emitted by cellular phones on the electroencephalogram during a visual working memory. *International Journal of Radiation Biology, 76,* 1659–1667.

Lai, H., Horta, A., Cho, C. K., & Guy, A. W. (1987). A review of microwave irradiation and actions of psychoactive drugs. *Engineering Medicine and Biology, 6,* 31–36.

Lebedeva, N. N., Sulimov, A. V., Suhmova, O. P., Kotrovskaya, T. T., & Gailus, T. (2000). Cellular phone electromagnetic field effects on bioelectric activity of human brain. *Critical Review of Biomedical Engineering, 28*, 323–337.

Marino, A. A. (1993). Electromagnetic fields, cancer, and the theory of neuroendocrine-related promotion. *Bioengineering, 29*, 255–276.

Marino, A. A., Bell, G. B., & Chesson, A. (1996). Low-level EMFs are transduced like other stimuli. *Journal of the Neurological Sciences, 144*, 99–106.

Mitchell, C. L., McRee, D. I., Peterson, N. J., Tilson, H. A., Shandala, M. G., Rudnev, M. I., Varetskii, V. V., & Navakatikyan, M. I. (1989). Results of a United States and Soviet Union project on nervous system effects of microwave radiation. *Environmental Health Project, 81*, 201–209.

Moulder, J. E., & Foster, K. R. (1995). Biological effects of power-frequency fields as they relate to carcinogenesis. *Proceedings of the Society for Experimental Biology and Medicine, 209*, 309–324.

Persson, B. R. R., Salford, L. G., & Brun, A., et al. (1997). Blood-brain barrier permeability in rats exposed to electromagnetic fields used in wireless communication. *Wireless Networks, 3,* 455–461.

Reiser, H.-P., Dimpfel, W., & Schober, F. (1995). The influence of electromagnetic fields on human brain activity. *Eur J Med Res, 1,* 27–32.

Repacholi, M. H. (1997). Radiofrequency field exposure and cancer what do the laboratory studies suggest? *Environmental Health Perspectives, 105, Suppl. 6,* 1565–1568.

Repacholi, M. H., Basten, A., Gebski, V., Noonan, D., Finnie, J., & Harris, A. W. (1997). Lymphomas in E mu-Piml transgenic mice exposed to pulsed 900 MHz electromagnetic fields. *Radiation Research, 147*, 631–640.

Riu, P. J., & Foster, K. R. (1999). Heating of tissue by near-field exposure to a dipole: A model analysis. *IEEE Transactions on Biomedical Engineering, 46*, 911–917.

Roschke, J., & Mann, K. (1997). No short term effects of digital mobile radio telephone on the awake human electroencephalogram. *Bioelectromagnetics, 18,* 172–176.

Shandala, M. G., Dumanski, U. D., Rudnev, M. I., Ershova, L. K., & Los, L. P. (1979). Study of nonionizing microwave radiation effects upon the central nervous system and behaviour reaction. *Environmental Health Perspectives, 30,* 115–121.

Sidorenko, A. V., & Tsaryk, V. V. (1999). Electrophysiological characteristics of the epileptic activity in the rat brain upon microwave treatment. In *Proceedings of conference on electromagnetic fields and human health* (pp. 283–284). Moscow.

Takashima, S., Onaral, B., & Schwan, H. P. (1979). Effects of modulated RF energy on the EEG of mammalian brain. *Radiation and Environmental Biophysics, 16*, 15–27.

Youbicier-Simo, B. J., & Bastide, M. (1999). Pathological effects induced by embryonic and postnatal exposure to EMFs radiation by cellular mobile phones (written evidence to IEGMP). *Radiation Protection, 1*, 218–223.