TETRA Mobile Radios interfere with Electroencephalography Recording Equipment

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Abstract

We observed an anomaly in the human electroencephalogram (EEG) associated with exposure to Terrestrial Trunked Radio (TETRA) Radiofrequency Fields (RF). Here we characterize the time and frequency components of the anomaly and demonstrate that it is an artifact caused by TETRA RF interfering with the EEG recording equipment and not by any direct or indirect effect on the brain.

Keywords: *terrestrial trunked radio (TETRA), Electroencephalography, Radio Waves/adverse effects, Telecommunications/instrumentation*

Introduction

Although it is well known that GSM mobile telephones may interfere with the recording of EEG, the effects of other telecommunications systems are much less well known. Terrestrial Trunked Radio (TETRA) is an open telecommunications standard for private mobile radios designed for use by the emergency services, utility companies and the military that is used in 121 countries around the world. TETRA uses time division multiplexing which means that the radio signal is transmitted in a series of timeslots that pulse at a rate of 17.6Hz[1]. One important consequence of this is that unlike GSM mobile phones, TETRA pulses at a frequency within the range of normal human electroencephalogram (EEG).

Whilst piloting a study into the effects that TETRA might have on human brain function, we found that placing a TETRA handset against the head could produce an anomaly in the EEG. This anomaly consisted of a series of spikes with a characteristic frequency of 17.6Hz. The spikes came in prolonged bursts that might last for several minutes and would usually only affect one or two channels. However, the anomaly was erratic and difficult to reproduce and small changes in the recording system, such as participant movement, could make it appear or disappear. The anomaly only ever occurred when the TETRA radio was on which suggests that whatever the cause, there appeared to be no enduring effect.

As TETRA RF has previously been shown to interfere with medical equipment[2], our initial interpretation was that the spikes were caused by interference between the TETRA radio and the EEG recording equipment. Consequently, we examined each component of the EEG recording setup in turn and, where possible, added shielding and determined its effect on the putative interference. However, it was difficult to quantify the effectiveness of the individual components of shielding with any precision because the spikes were difficult to reproduce reliably. As some components of the recording system were already shielded or were outside of the Faraday chamber in which the EEG recordings were made, we focussed on those that were unshielded and exposed to the signal. These included the scalp/electrode interface, the leads between the electrodes and the pre-amplifier and the pre-amplifier itself.

It was not possible to shield effectively the scalp/electrode interface but we were able to compare several commercially available electrode caps with different shapes and types of electrode. The anomaly was detected in at least some recordings with all those we tried but sintered Ag/AgCl electrodes were marginally superior to tin ones. Overall, however, the shape and type of electrode made little difference to the presence or magnitude of the spikes.

We also added ferrite sleeves to cables and at interfaces to reduce both incoming and outgoing RF interference. Several types of ferrite suppressor were tested but a ferrite sleeve placed just outside the pre-amplifier proved to be the most effective. In addition, we replaced the standard unshielded leads with co-axial leads and this produced some additional but modest benefit.

Initial amplification of the EEG signal was performed by pre-amplifiers positioned within 1m of the participant's head housed in a plastic box. This offered no effective protection from the RF so, we encased the pre-amplifiers in a Faraday cage and this resulted in a noticeable reduction in the occurrence of the anomaly. In addition, we added pi-network feed-through filters (low-pass filters for eliminating high frequency RF interference) where the electrode leads passed through the Faraday cage enclosing the pre-amplifier and this had a beneficial effect too as suggested in[3].

Despite the shielding however, the TETRA-related spikes continued to appear in at least one channel in some EEG recordings. This meant that either the shielding had been only partially effective or that the TETRA RF signal might was having a direct effect on the brain. This question is considerable importance because although there is no published scientific evidence to suggest that either TETRA handsets [4-6] or TETRA base-stations [7] pose a risk to human health, there exists a high level of concern amongst some groups in the community about the safety of TETRA (see, for example, TETRAWATCH at http://www.tetrawatch.net/main/index.php).

Consequently in order to determine whether the anomaly was due to TETRA directly interfering with the EEG recording equipment or to some unknown biological effect, we compared EEG recordings obtained from human participants with those obtained from a phantom head. If the anomaly was seen only in human recordings it would suggest that the anomaly was biologically mediated but if the same anomaly was seen in both human and phantom recordings then it must be an electronically mediated effect.

Methods

We recorded EEG from 164 police officers (24 women) with a mean age of 39 years (s.d.=7.3; range=22-62) recruited from across the UK. All participants gave their written informed consent and the study was approved by North West Medical Research Ethics Committee.

EEG was recorded from both the participants and a phantom head from 28 scalp sites using an FMS Easy-Cap with Ag/AgCl sintered ring electrodes referenced to the left ear with a ground electrode placed 1.5 cm anterior to the vertex. Recording and digitization were carried out using a Neuroscan Synamps-II amplifier, powered from the mains, with signal bandpass 0.15–100Hz and sampling rate of 500 Hz. Impedances were measured using an impedance meter and kept below 5kΩ. Frequency analysis was by multi-taper FFT[8] using de-trended EEG epochs of 2.048s. Time analysis was performed using the method of event-related potentials which involved selecting segments of EEG centred on the peak amplitude of each spike, ranging from 100ms before the spike to 100ms afterwards, and averaging across all occurrences.

Human recordings were obtained from the participants in a number of different experimental conditions but, as the anomaly was identical in them all, only the results from EEG recorded in a resting state with eyes closed are reported here. The human recordings were all made with the EEG recording system shielded against interference in the way outlined in the introduction.

The phantom head was made from a 2mm thick fibreglass head shape that was designed to measure the Specific Absorption Rate (SAR) from mobile phones. The phantom was filled with a super-saturated solution of sucrose and salt that gave it comparable permittivity and conductivity to a human head, but as fibreglass is a poor conductor, the electrode impedances were much higher. To overcome this, we covered the phantom head with a saline-soaked towel which increased conductivity and produced impedances comparable to those seen in human recordings (i.e. $<5k\Omega$). To simulate multiple participants with the phantom, between each recording, the EEG cap, leads and the TETRA radio were completely removed before being replaced. This was repeated 35 times to simulate 35 separate recordings. The recordings with the phantom head reported here were made with EEG recording system without any added shielding.

TETRA RF was generated using a specially commissioned handset that transmitted at 390-400MHz[9] and was calibrated to give a peak SAR of 1.3 W kg^{-1}. The radio was placed on the left-hand side of the head in a position that might be used when making a call (Figure 1). Maximum SAR was generated close to the antenna [10] which ran from just posterior to electrode T7 to midway between P7 and CP5.

Results

The peak-to-peak amplitude of the anomaly varied considerably between recordings and, when the amplitude was low, it was difficult to be sure whether the anomaly was present or not. For this reason an objective criterion for the presence or absence of the anomaly was defined based upon the ratio of the power observed in the signal at the 2nd harmonic (35.2Hz +/-1Hz) to the mean of the power in the signal at 33.2Hz+/-1Hz and 37.2+/1Hz. The rationale for this was that, in the absence of TETRA interference, power at 35.2Hz ±1Hz would be approximately equal to the mean of the power in the adjacent frequency bands and give a ratio~1.0 but be higher otherwise. The 2nd harmonic was chosen rather than the 1st harmonic because the normal variability in human EEG is much lower at the higher frequency and because, whenever the anomaly was present at the fundamental frequency, it was invariably present at higher harmonics. This power ratio was calculated for each participant and for each channel when the TETRA radio was switched off was and the distribution of the maximum values obtained from each person was examined. The cut-off for identifying the presence of the anomaly was defined as the 95th percentile of the distribution of the maximum value of this ratio obtained from each individual which was found to be 1.16. This means that fewer than 5% of individual EEG recordings would be expected to exceed the cut-off in any channel when there was no TETRA signal present.

Using this criterion, and despite shielding, the TETRA-related anomaly was seen in ~2% of channels recorded (89 channels of the 4592 recorded in the study) and affected at least one channel in 49 out of the 164 participants (30%). The peak-to-peak amplitude of the anomaly varied considerably between recordings, ranging from 0.5μV to 150μV with most <10μV. The ratio of power at the 2nd harmonic (35.2Hz +/-1Hz) to the mean of the power at adjacent frequencies (33.2Hz+/-1Hz and 37.2+/1Hz) in the affected channels ranged from 1.16 (i.e. the cut-off value) to 4.13 with a median value of 1.28. The spikes could be predominantly positive or negative but whenever and wherever they occurred, their shape and frequency was very consistent. For the phantom recordings, which were made with the unshielded EEG equipment, the anomaly was seen at nearly every electrode site on every recording and was uniformly distributed across the scalp. For the human recordings, however, because the EEG equipment was shielded, most electrode channels were unaffected throughout most of the recordings. Figure 2 shows the frequency of occurrence of the anomaly at each scalp site for the human EEG recordings. The anomaly was seen most often at electrodes PO3 and Oz and proximity to areas of maximum field strength did not appear to be critical as those electrodes closest to the antenna [10] such as T7, P7 and CP5 were among the least often affected. However, increasing the distance between the head and the antenna by placing the handset on the lapel, which typically increased the separation 20cm or more, did have a significant impact and no interference was seen in any recordings with the radio in this position.

An example of a 2s section of the EEG anomaly recorded from a human participant is shown in Figure 3a). The example shown here was the worst case seen and shows peak-to-peak voltage differences in excess of 150μV. Figure 3b) shows three cycles of the average time course of the same signal with a 56.6ms interval between peaks, corresponding to 17.6Hz, the frequency of the TETRA pulse. Figures 3c) and 3d) show recordings from the phantom head comparable to Figures 3a) and 3b) respectively. Figure 3e) shows the log-amplitude frequency spectra for the same recordings for both the human and phantom recordings.

Discussion

It is clear that the shape and time course of the anomaly was the same in both the human and phantom recordings (Figures 3a and 3c). This view is confirmed by the time-averaged signals which again show identical shape and inter-peak interval in the human and phantom recordings (Figures 3b and 3d). The similarity between the human and phantom recordings also extended to the frequency domain as can be seen in Figure 3e and both human and phantom recordings showed spectral peaks at 17.6Hz, the pulsing rate of TETRA, and at integer multiples of 17.6Hz.

There were, however, some differences. For example, the alpha rhythm, which is the dominant frequency in the waking EEG (~10Hz), was seen in the human recordings but was not present in the phantom recordings. Apart from this, however, there were no spectral peaks in the human recordings that were not also seen in the phantom recordings. There were, however, multiple spectral peaks present in then phantom recordings that were absent or much attenuated in the human recordings. These were all related to either 50Hz line noise or to displaced harmonics of the TETRA signal. Both human and phantom recordings showed a spectral peak at 50Hz but the phantom recordings also showed line noise-related peaks at 75, 100, 125, 150, 175, 225 and 200Hz. The phantom recordings also showed two series of spectral peaks that were not present in the human recordings in which each peak in the series was separated by precisely 17.6Hz which clearly identifies them as originating from the TETRA signal. One of these harmonic series was displaced by -12.7Hz (4.8, 22.5, 40.0, 57.7….235Hz) and in the other by -4.9Hz (12.7, 30.3, 47.9, 65.5….242Hz). The reason for these differences in the phantom and human recordings is that the phantom recordings were made with the unshielded equipment whereas the human recordings were shielded. It seems that the shielding was effective at eliminating higher harmonics of line noise and the displaced harmonics of the TETRA signal than even though it did not completely eliminate the integer harmonics of the TETRA signal. The difference in the shielding of the phantom and human recordings is also the most likely explanation for the variation seen in the topographical distribution of the anomaly. For the phantom recordings, the anomaly occurred in most recordings and was usually present in all channels. In contrast, 70% of the human recordings were anomaly free and, when it did occur, it was not uniformly distributed across the scalp (Figure 2). Notwithstanding these differences, the identical time course and pattern of spectral peaks at 17.6Hz and its integer harmonics, in both the human and phantom recordings show that the anomaly is caused by TETRA RF interfering with the EEG recording equipment and not by any effect on the brain or other human tissue.

The time and frequency characteristics of the anomaly, together with its sporadic occurrences, are such that it is conceivable that it could be mistaken for abnormal human EEG. However, given that the anomaly only occurred when the TETRA handset was placed against the participant's head, it is unlikely that such an error would be made in clinical practice. Nevertheless, given high levels of concern about the effects of TETRA on human health, it is important to be able to demonstrate that, whatever effects TETRA may or may not have on its users, this anomaly is not one of them.

Conclusion

TETRA radios can produce an anomaly in EEG recordings with spikes occurring at a frequency of 17.6Hz matching the pulsing rate of the TETRTA RF signal. The presence of the identical spikes in both human and phantom recordings shows that this is an artifact caused by direct interference between the TETRA-RF and the EEG recording equipment and is not a biologically mediated effect.

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Declarations

Competing interests: None declared

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Ethical Approval: The study was approved by North West Medical Research Ethics Committee Ref no 03/8/111

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Figure Captions

Figure 1. Showing the position of the TETRA radio relative to the EEG Electrodes

Figure 2. Showing the number of times the anomaly was seen at each of the 28 electrode sites on the scalp. The size of the circle indicates the number of human EEG recordings in which the anomaly was present. The light grey rectangle gives the approximate position of the antenna.

Figure 3. a) Two seconds of raw EEG from a human recording showing a sequence of spikes occurring with a frequency of 17.6Hz. This example is from the most severely affected case where peak-to-peak amplitude was up to 150 μV. In this example spikes showed a strong positive deflection but negative spikes were also seen. b) Averaged data from the same individual showing highly regular pulses occurring every 56.6ms equivalent to 17.6Hz. The time component of the signal was estimated by averaging segments of EEG centred on the peak of the spikes shown in a). c) Two seconds of raw EEG from a phantom recording showing a similar pattern to the human recording with a sequence of spikes occurring with a frequency of 17.6Hz. d) Averaged data from the same phantom recording showing the same shape and interval between spikes as the human recording. e) Log-amplitude spectrogram of EEG from both human and phantom recordings. Note the spectral peak at 17.6Hz and at higher harmonics for both human and phantom recordings. The spectrogram was based on approximately 4 minutes of EEG.