The Effects of Electromagnetic Fields Emitted by Mobile Phones on Human Sleep and Melatonin Production

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Abstract

The use of mobile phones is continually increasing throughout the world, with recent figures showing that there are currently more than 2 billion mobile phone users worldwide. However, despite the recognised benefits of the introduction and widespread use of mobile phone technologies, concerns regarding the potential health effects of exposure to the radiofrequency electromagnetic fields emitted by mobile phone handsets have similarly increased, leading to an increase in demand for scientific research to investigate the possibility of health effects related to the use of mobile phones.

An increasing amount of radiofrequency bioeffects research related to mobile phone use has focussed on the possible effects of mobile phone exposure on human brain activity and function, particularly as the absorption of energy in the head and brain region is much higher than in other body regions, which is a direct result from the close proximity of the mobile phone to the head when in normal use. In particular, the use of sleep research has become a more widely used technique for assessing the possible effects of mobile phones on human health and wellbeing, and is particularly useful for providing important information in the establishment of possible radiofrequency bioeffects, especially in the investigation of potential changes in sleep architecture resulting from mobile phone use.

A review of the previous literature showed that a number of studies have reported an increase in the electroencephalogram spectral power within the 8 – 14 Hz frequency range in both awake and sleep states following radiofrequency electromagnetic field exposure. In regards to sleep, the enhancements reported have not been entirely consistent, with some early studies failing to find an effect, while more recent studies have reported that the effect differs in terms of particular frequency range. However, in general the previous literature suggests that there is an effect of mobile phone

emissions on the sleep electroencephalogram, particularly in the frequency range of sleep spindle activity.

In addition to changes in spectral power, changes in other conventional sleep parameters and the production and secretion of melatonin have also been investigated, however, there has been little or no consistency in the findings of previous studies, with the majority of recent studies concluding that there is no influence of mobile phone radiofrequency fields on these parameters of sleep or melatonin.

Following a detailed review of the previous research, the current study was developed with the aim to improve on previous methodological and statistical limitations, whilst also being the largest study to investigate mobile phone radiofrequency bioeffects on human sleep. The principle aims were thus to test for the immediate effects of mobile phone radiofrequency electromagnetic fields on human sleep architecture and the secretion of the pineal hormone, melatonin.

The experiment included 50 participants who were randomly exposed to active and sham mobile phone exposure conditions (one week apart) for 30 minutes prior to a full night-time sleep episode. The experimental nights employed a randomised exposure schedule using a double-blind crossover design. Standard polysomnography was used to measure subsequent sleep, and in addition, participants were required to provide urine samples immediately following exposure and upon waking in the morning. A full dosimetric assessment of the exposure system was also performed in order to provide sufficient details of the exposure set-up used in the current thesis and to account for the lack of detailed dosimetric data provided in the majority of previous studies.

The results of the current study suggest that acute exposure to a mobile phone prior to sleep significantly enhances electroencephalogram spectral

power in the sleep spindle frequency range compared to the sham exposure condition. The current results also suggest that this mobile phone-induced enhancement in spectral power is largely transitory and does not linger throughout the night. Furthermore, a reduction in rapid eye movement sleep latency following mobile phone exposure was also found compared to the sham exposure, although interestingly, neither this change in rapid eye movement sleep latency or the enhancement in spectral power following mobile phone exposure, led to changes in the overall quality of sleep. Finally, the results regarding melatonin suggested that, overall, overnight melatonin secretion is unaffected by acute exposure to a mobile phone prior to sleep.

In conclusion, the current study has confirmed that a short exposure to the radiofrequency electromagnetic fields emitted by a mobile phone handset immediately prior to sleep is sufficient to induce changes in brain activity in the initial part of sleep. The consequences or functional significance of this effect are currently unknown and it would be premature to draw conclusions about possible health consequences based on the findings of the current study.

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Finally, I would like to thank Glenn for all of his love and support throughout this PhD. Thanks for always being able to make me smile and for always believing in me – I could not have come this far without you!

Declaration

I declare that this thesis does not incorporate, without written acknowledgement, any material that has previously been submitted for the award of any other degree or diploma in any university, college, or other educational institution.

To the best of my knowledge, this thesis does not contain any material previously published or written by another person except where due reference is made in the text, including the disclosure of contributions for any work based on joint research or publication.

I declare that the ethical principles and procedures specified in the Swinburne University of Technology Human Research Ethics document on human research and experimentation have been adhered to in the presentation of this thesis.

Sarah Loughran

Signed_____

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Peer-Reviewed Journal Publications[1]:

Loughran, S.P., Wood, A.W., Barton, J.M., Croft, R.J.,Thompson, B., Stough, C. The effect of electromagnetic fields emitted by mobile phones on human sleep. *Neuroreport,* 16:1973-1976 (2005).

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Peer-Reviewed Conference Proceedings:

Loughran, S.P., Wood, A.W., Croft, R.J., Thompson, B., Stough, C. The effects of electromagnetic fields emitted by GSM mobile phones on human sleep parameters. Australian Journal of Psychology 56: 47-47 Suppl. S, (2004).

Loughran S.P., Wood A.W., Barton J.M., Croft R.J., Thompson B., Stough, C. The Effects of Electromagnetic Fields Emitted by GSM Mobile Phones on Human Sleep. Bioelectromagnetics 2005, June 19-24, Dublin, Ireland.

Loughran SP, Wood AW, Barton JM, Croft RJ, Thompson B, Stough C. The Effects of Electromagnetic Fields Emitted by GSM Mobile Phones on Human Sleep. ASA and ASTA 18th Annual Scientific Meeting, Surfers Paradise Marriot Resort, October 7-9, 2005.

Loughran, S.P. Phone exposure effects on sleep physiology. Monte Verità workshop on EMF Health Risk Research, November 20-24, 2005, Switzerland.

Loughran, S.P. The Effect of Electromagnetic Fields Emitted by Mobile Phones on Human Sleep. World Health Organization (WHO) & Australian Centre for RF Bioeffects Research Regional Workshop on Radio frequency fields: Health Effects & Policy Options for Protection. November 17-18, 2005, Melbourne, Australia.

[1] See appendix G for copies of the peer-reviewed journal publications

Loughran, S.P., Wood, A.W., Croft, R.J., Barton, J.M.,Thompson, B., Stough, C. The influence of mobile phone electromagnetic fields on the human sleep EEG over an entire night. Bioelectromagnetics 2006, June 11-15, Cancun, Mexico.

Loughran, S.P., Wood, A.W., Stough, C. The Effects of Evening Mobile Phone Use on Subsequent Melatonin Production. Bioelectromagnetics 2006, June 11-15, Cancun, Mexico.

Loughran, S.P., Wood, A.W., Croft, R.J., Barton, J.M.,Thompson, B., Stough, C. The time-course of the effect of mobile phone electromagnetic fields on the human sleep EEG. Sleep and Biological Rhythms 2006; 4: A18–A56.

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List of Abbreviations

1G	First generation mobile phone technology
2G	Second generation mobile phone technology
3G	Third generation mobile phone technology
6-OHMS	6-hydroxymelatonin sulfate
A	Amps
AM	Amplitude modulated
aMT6s	6-sulphatoxymelatonin
ANOVA	Analysis of variance
APC	Adaptive power control
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
CDMA	Code Division Multiple Access
Cr	Creatinine
DASY	Dosimetric Assessment System
DCS	Digital Communication System
DTX	Discontinuous transmission
ECG	Electrocardiogram
EDF	European Data Format
EEG	Electroencephalogram
ELF	Extremely low frequency
EME	Electromagnetic energy
EMF	Electromagnetic field
EMG	Electromyogram
EOG	Electro-oculogram
ERD	Event-related desynchronisation
ERP	Event-related potential
ERS	Event-related synchronisation
ESDS	Eastern Sleep Disorders Service
FDTD	Finite-difference time domain
FEM	Finite element method
FFT	Fast Fourier transform
FM	Frequency modulated
GABA	Gamma-aminobutyric acid
GH	Growth hormone
GHz	Gigahertz
GSM	Global System for Mobile Communications
Hz	Hertz
IAF	Individual alpha frequency
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation Protection

IEEE	Institute of Electrical and Electronics Engineers, Inc
IEGMP	Independent Expert Group on Mobile Phones
J	Joules
KHz	Kilohertz
LH	Luteinising hormone
LOC	Left outer canthus
MHz	Megahertz
MOM	Method of moments
MRI	Magnetic resonance imaging
NEO-PI-R	The Revised NEO Personality Inventory
NHMRC	National Health and Medical Research Council
NREM	Non-rapid eye movement sleep
PET	Positron emission tomography
PLMs	Period limb movements
POMS	The Profile of Mood States
PSG	Polysomnography
$p\eta^2$	Partial eta squared
rCBF	Regional cerebral blood flow
REM	Rapid eye movement sleep
RERA	Respiratory effort-related arousals
RF	Radiofrequency
ROC	Right outer canthus
SAM	Specific Anthropomorphic Mannequin
SaO_2	Oxygen saturation
SAR	Specific absorption rate
SART	Sustained Attention to Response Task
SCN	Suprachiasmatic nucleus
SD	Standard deviation
SEM	Standard error of measurement
SI	International system of units
sIgA	Immunoglobulin A
SPSS	Statistical Package for the Social Sciences
SWA	Slow-wave activity
SWS	Slow-wave sleep
T	Tesla
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
V	Volts
W	Watts
WASO	Waking after sleep onset
WHO	World Health Organisation

Chapter 1: Introduction

1.1 Introduction and Background

The use of mobile phone technology is continually increasing throughout the world, with recent figures showing that there are currently more than 2 billion users worldwide (GSMWorld, 2006), and that mobile phone connections also outnumber those of the older fixed-line system (Repacholi, 2001). However, despite the recognised benefits of the introduction and widespread use of mobile phone technologies, concerns regarding the potential health effects of exposures to the radiofrequency (RF) fields emitted by mobile phone handsets have also increased, leading to an increase in demand for scientific research to investigate the possible health effects of exposure to mobile phone technologies. Given the widespread use of mobile phones, and the trend for developing countries to establish this technology in preference to the more expensive fixed-line systems, any adverse health effects from mobile phone use could have a significant impact on public health (Repacholi, 2001).

Although RF fields are present in numerous technologies used in everyday life, such as radio and television, the rapid introduction of mobile phones among the general public and the relatively near-field RF exposure to the head that occurs during normal use, makes it a necessity for the possibility of adverse health consequences to be thoroughly assessed. In response to this rapid increase in the use of and concerns surrounding mobile phone use, the World Health Organisation (WHO) established the International Electromagnetic Field (EMF) Project in 1996 in order to provide a coordinated international response to concerns about possible health effects of exposure to EMF and to assess the scientific literature and identify gaps in

knowledge that require further investigation to improve health risk assessments.

In order to provide adequate health risk assessment of exposure to mobile phone RF EMF, a number of different research approaches are required, as different study types are designed to address different aspects of the problem and overcome different limitations. The main research approaches that have been used for determining RF bioeffects from exposure to mobile phones are *in vitro* studies, epidemiological studies, and *in vivo*, animal, or human volunteer studies. *In vitro* studies are best suited to providing insight into mechanisms for biological effects from RF EMF exposure, while epidemiological studies are particularly useful in providing direct information on the possible associations between adverse health and mobile phone use in the population. Although both approaches have play an important role in RF bioeffects research, they are also limited in that *in vitro* studies tend to focus on the individual constituents (such as biological tissue or cells) of an organism and therefore are unable to provide information on RF EMF effects on an organism as a whole, while epidemiological studies also suffer from weaknesses in interpretation, particularly when low relative risks are reported (WHO, 2006), and cannot address the issue of causation. Conversely, *in vivo* studies (either animal or human studies) are thought to provide more convincing evidence of adverse health consequences as the RF EMF exposure is applied to a whole, living organism, allowing results to be generalised to whole living organisms and the complexity of processes associated with them.

Particularly in regards to human laboratory studies, a large proportion of these studies have concentrated on the possible effects of mobile phone RF EMF on neurophysiology and cognition, due to the close proximity of a mobile phone to the human head when conventionally used, and the resultant absorption of RF energy in the human brain. Although a variety of measures have been used to assess these possible effects, the most

common technique that has been used in studies examining potential physiological effects of mobile phone radiation on human brain activity and function is the electroencephalogram (EEG) (Cook et al., 2006). Additionally, as mobile phone-induced changes to the EEG have been observed in a number of research studies (see sections 4.3 and 6.2 for review), the WHO has highlighted the investigation of acute effects of mobile phone RF EMF on human cognition and the EEG, particularly in children and adolescents, as a high priority research need in their latest research agenda for RF fields (WHO, 2006).

1.2 The Electroencephalogram

The EEG is a non-invasive neurophysiologic measurement of the electrical activity of large numbers of neurons in the brain, recorded from electrodes placed on the scalp. The electrodes are used to detect and record voltage fluctuations, which correspond to variations in electrical potential between different locations in the brain. The EEG is one of only a few techniques that provides high temporal resolution, capable of detecting changes in electrical activity in the brain with millisecond precision (Debener et al., 2006). The EEG is particularly useful as a measure of behavioural state (i.e. sleep or wakefulness) and is also often used as an important clinical tool for monitoring and diagnosing neurophysiologic-related disorders, such as epilepsy, brain damage, and various sleep disorders. The EEG is also commonly used as a measure of brain functioning, as variations in frequency and amplitude can be observed during changes in cognitive state or in response to various stimuli.

Historically, the most common way of quantifying the EEG is to divide the frequency spectrum into discrete ranges, with the four major ranges referred to as alpha, beta, theta, and delta.

Alpha activity is the dominant frequency in the adult EEG (Klimesch, 1999) and is typically characterised by waveforms between 8 and 13 Hz that are best recorded at occipital and parietal sites of the brain. Alpha rhythms are most easily detected with the eyes closed and are generally attenuated by opening the eyes or during drowsiness or sleep. It has also been shown that alpha activity is a sensitive measure for cognitive performance or cognitive processing capacity, and that alpha frequencies vary between individuals (referred to as individual alpha frequency, IAF) and also as a function of age, neurological disease, memory performance, brain volume, and task or cognitive demand (Klimesch, 1999). Alpha is also the frequency band at which most mobile phone-related effects have been observed.

Beta activity is of a higher frequency than alpha, and is characteristically observed between 13 and 25 Hz. It is most commonly associated with wakefulness and increased activation and arousal. In contrast, the theta and delta bands are comprised of activity that is of a lower frequency than the alpha and beta bands, and are most commonly associated with sleep. Theta activity comprises rhythms between 4 and 8 Hz and can be seen in all stages of non-rapid eye movement sleep. Delta activity comprises rhythms up to 4 Hz that are widely distributed in the cortex. Delta activity is most commonly seen during deeper stages of sleep and is also generally absent in healthy awake adults.

One of the most common methods for quantifying the EEG is via spectral analysis using the fast Fourier transform (FFT), which has been the predominant method used for EEG analysis in RF bioeffects research. The FFT transforms the time-dependent fluctuations in EEG amplitude into frequency-dependent fluctuations in amplitude, by representing each waveform as a series of sinusoidal components of different frequencies, with the sum of the sinusoids resulting in the original waveform. One requirement of the FFT is that signal being analysed is stationary, and although EEG waves during sleep are not stationary, the FFT is still an appropriate analysis

method as by dividing the EEG into short time frames or epochs (for example, 4 seconds), a quasi-stationary signal can be obtained for each of these epochs (Knoblauch, 2004). The only other requirement for FFT is that the number of points to be analysed in the series is of a power of 2. Overall, the FFT is generally viewed as a useful EEG analytic technique that is fast and able to differentiate frequency, amplitude, and other elementary characteristics of the EEG waveform.

1.3 Summary of the EEG in mobile phone research and overview and rationale for the current study

Overall, the EEG has been a popular tool in previous research on mobile phone-related bioeffects, and given that the different types of brain activity are well characterised (particularly during sleep states) and that the EEG provides a direct measurement of electrical activity with a high temporal resolution, it remains an important device for investigating possible mobile phone-induced effects on the brain, cognition, and sleep.

However, while the EEG has become widely used as a measure to investigate possible effects of mobile phone exposure, the lack of consistency between previous studies has prevented any firm conclusions being drawn regarding mobile phone-induced changes to brain activity and human sleep. Due to this, the current study was designed to specifically investigate the influence of mobile phone RF EMF on human sleep and the sleep EEG. Following a detailed review of the previous research, the current study was developed with the aim to improve on previous methodological and statistical limitations, whilst also being the largest study to our knowledge to investigate mobile phone RF bioeffects on human sleep. Therefore, the current study would also provide the strongest evidence to date of the nature and extent of a mobile phone-related effect on human sleep and the sleep EEG. Specifically, the current study intended to address two main research

questions: 1) Is human sleep affected by acute exposure to the RF EMF emitted by a mobile phone handset, and if so, which aspects of human sleep are affected? 2) Does acute exposure to the RF EMF emitted by a mobile phone handset affect melatonin production and secretion, and if so, what is the nature of this effect?

Chapter 2: Sleep and the Brain

This chapter begins with a general introduction to the structure of human sleep, providing a detailed background on the defining characteristics of human sleep and highlighting the measurement and assessment techniques used in defining human sleep stages. A brief description of the important physiological changes and neurotransmitter activity associated with the initiation and maintenance of human sleep is provided, followed by a discussion of the role of melatonin in the human sleep-wake cycle. The chapter concludes with a brief introduction to the main theories behind the importance and functions of human sleep.

2.1 Sleep Structure

Normal human sleep consists of two distinct phases – non-rapid eye movement (NREM) and rapid eye movement (REM) sleep – that alternate in a regular pattern throughout the night. NREM sleep is typically divided into four stages (known as stage 1, 2, 3 and 4) that are defined by distinct differences in the electroencephalogram (EEG). The EEG during NREM sleep has a synchronous pattern and is characterised by specific waveforms, such as sleep spindles and k-complexes (see section 2.2). NREM sleep is also characterised by slow-wave activity (SWA), which is EEG activity in the frequency range of approximately 0.5 Hz to 4.5 Hz, and also referred to as 'delta activity' or 'delta waves' (Kryger et al., 2005). The level of SWA in the EEG is regulated by the amount of prior sleep and waking, and is also an indicator of sleep homeostasis in NREM sleep (Kryger et al., 2005). The four stages of NREM sleep are also a representation of sleep depth, with stage 1 sleep typically considered as light sleep and having a low arousal threshold, and stage 4 sleep representing deep sleep with a high arousal threshold

(Kryger et al., 2005). In contrast, REM sleep is characterised by the appearance of low voltage, mixed frequency EEG activity and episodic bursts of rapid eye movements in the electrooculogram (EOG).

Normal human sleep begins in stage 1 NREM sleep and then progresses through stages 2, 3, and 4 NREM sleep before entering REM sleep. This NREM - REM sleep pattern continues cyclically throughout the night, with each cycle lasting approximately 90 - 110 minutes. On average, a person will have between 3 and 5 complete NREM-REM sleep cycles during a typical night of sleep. Over the course of a night, the distribution of sleep stages across these cycles gradually changes. Cycles that are early in the night are typically shorter and are characterised by a larger proportion of stages 3 and 4 sleep (also collectively known as slow-wave sleep, SWS), and relatively short REM sleep episodes. In contrast, as the night progresses, the amount of SWS decreases and may disappear completely as stage 2 sleep becomes the predominant NREM sleep stage, and REM sleep episodes become longer (Figure 1).

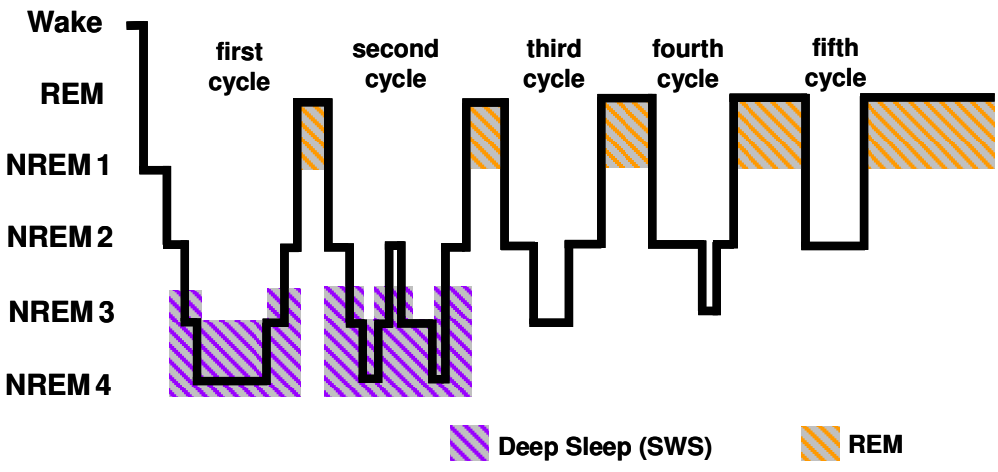

Figure 1. *The sleep cycle of a normal healthy adult and the sequence of states and stages of sleep during a typical night.*

Sleep architecture, however, is highly dependent on age, particularly in relation to the proportions of NREM and REM sleep in each cycle and the total sleep time (Kryger et al., 2005). In general, over the course of a lifetime there is a reduction in total sleep time and sleep efficiency (or the ratio of total sleep time to time spent in bed), and a decrease in the proportion of REM sleep (Kryger et al., 2005). Aging also produces changes within NREM sleep (independent of the changes in REM sleep), with increases in the percentage of stage 1 sleep and a reduction in the percentage of stages 3 and 4 sleep or time spent in slow wave sleep being common.

2.2 NREM Sleep Stages

The four stages that comprise NREM sleep are defined by specific patterns and differences in EEG activity (see Figures 2 - 5). Stage 1 sleep is most frequently associated with the transition from wakefulness to sleep, and can also often appear following body movements or changes in position during sleep. It is characterised by relatively low-voltage, mixed frequency EEG activity, and vertex sharp waves are also common (Figure 2) (Rechtschaffen and Kales, 1968). The transition from wakefulness to stage 1 sleep is also characterised by slow eye movements in the EOG, which are of several seconds duration and generally occur 1 to 2 minutes before the onset of stage 1 sleep (Kryger et al., 2005). Although muscle tone is generally maintained during NREM sleep stages, there can be a small reduction in the electromyogram (EMG) amplitude during this transition.

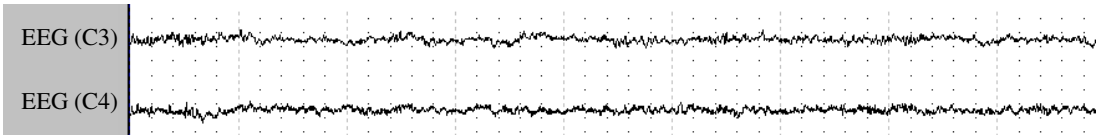

Figure 2. *An example of the EEG during stage 1 sleep.*

Stage 2 sleep is characterised by background EEG activity similar to that of stage 1 sleep, with a relatively low voltage and mixed frequency EEG (Figure 3). However, stage 2 sleep is distinguished from stage 1 sleep by the presence of two unique patterns in the EEG, known as sleep spindles and k-complexes (Figure 3). Sleep spindles are often seen in low voltage background EEG and can also be superimposed on delta activity or temporally locked to a vertex sharp wave or to a k-complex (De Gennaro and Ferrara, 2003). Rechtschaffen and Kales (1968) defined sleep spindles as bursts of brain activity between 12 Hz and 14 Hz that are characterised by groups of rhythmic waves with progressively increasing amplitude, followed by a gradually decreasing amplitude for a duration of at least 0.5 seconds. However, the frequency range of sleep spindles in this standard definition is often regarded as being too narrow as sleep spindles have been observed as high as 16 Hz and sometimes even lower than 10 Hz (Jankel and Niedermeyer, 1985; Zeitlhofer et al., 1997). It has recently become accepted that there are two types of sleep spindles that are topographically and spectrally distinct. This was first observed by Gibbs and Gibbs (1950), who reported that spindles around 12 Hz, or low frequency spindles, were more prominent in frontal areas, whereas spindles around 14 Hz, or high frequency spindles, were more pronounced at central and parietal derivations (Gibbs and Gibbs, 1950). This frequency-specific topographic difference in spindle activity has been confirmed by a number of more recent studies (Jobert et al., 1992; Werth et al., 1997; Zeitlhofer et al., 1997; Zygierewicz et al., 1999; Ueda et al., 2001; Doran, 2003) and the different spindle types have also been shown to be differentially affected by factors such as endogenous circadian phase (Dijk and Czeisler, 1995), and menstrual cycle phase (Driver et al., 1996). Although the frequency domain of sleep spindles is rather complex and there is large inter-individual variation in the occurrence of sleep spindles, in general, in normal adults, sleep spindles occur at a rate of approximately 3 to 8 spindles per minute, and the rate at which they occur within individuals appears to be fairly stable (Gaillard and Blois, 1981).

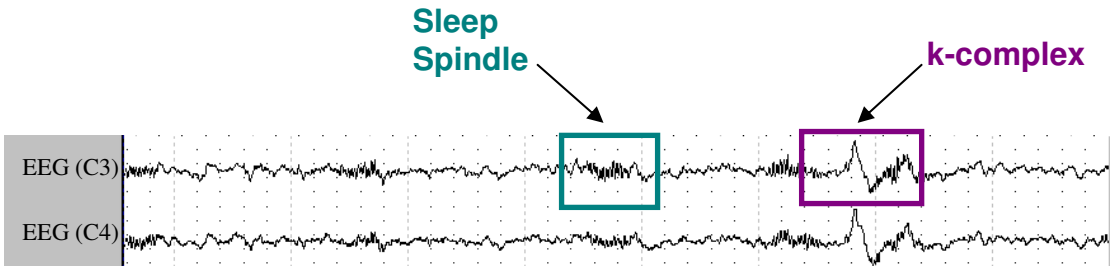

Figure 3. *An example of the EEG during stage 2 sleep.*

The other characteristic EEG pattern of stage 2 sleep, the k-complex (Figure 3) is defined as an EEG wave form that has "a well delineated negative sharp wave which is immediately followed by a positive component" (Rechtschaffen and Kales, 1968). The negative component of the k-complex, like the different types of spindle activity, is topographically distributed and is maximal at frontal areas (Colrain, 2005). K-complexes are distinct from the background EEG activity and must exceed 0.5 seconds in duration to be classed as a k-complex. The rate of k-complexes varies widely among individuals and they can either occur spontaneously or be generated following an auditory stimulus (Kryger et al., 2005).

Stage 3 sleep consists of at least 20% of high voltage, SWA in the EEG, but no more than 50% in an epoch (Figure 4). When the EEG contains more than 50% of SWA this is considered to be stage 4 sleep (Figure 5). Sleep spindles and k-complexes can also occur during stages 3 and 4 sleep (SWS), but unlike in stage 2 sleep, they are generally not distinct from the background EEG activity.

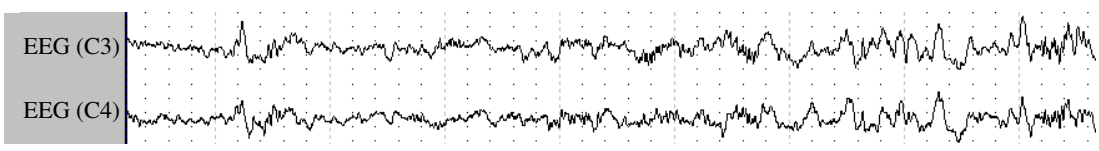

Figure 4. *An example of the EEG during stage 3 sleep.*

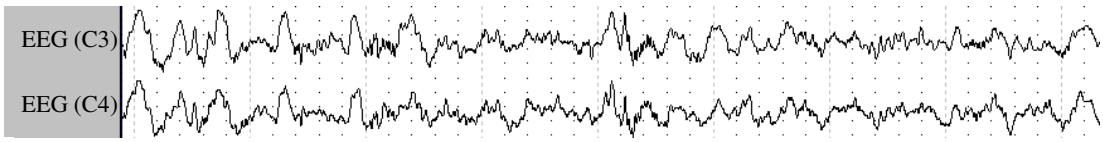

Figure 5. *An example of the EEG during stage 4 sleep.*

2.3 REM Sleep

The EEG of REM sleep is characterised by the appearance of relatively low-voltage, mixed frequency activity (Rechtschaffen and Kales, 1968), and at times may also contain distinctive "sawtooth" waves, which predominantly occur at the vertex and in conjunction with eye movements (Figure 6). In addition to desynchronised EEG activity, REM sleep is also distinguished by bursts of rapid eye movements as recorded in the EOG, and also suppression of EMG activity. The bursts of rapid eye movements occur at intervals throughout the REM sleep phase, and the number of rapid eye movements tends to increase with each subsequent REM sleep episode in the course of the night (5). Changes in sleeping posture or position are also fairly common occurrences during the transition between NREM and REM sleep episodes (Dement and Kleitman, 1957).

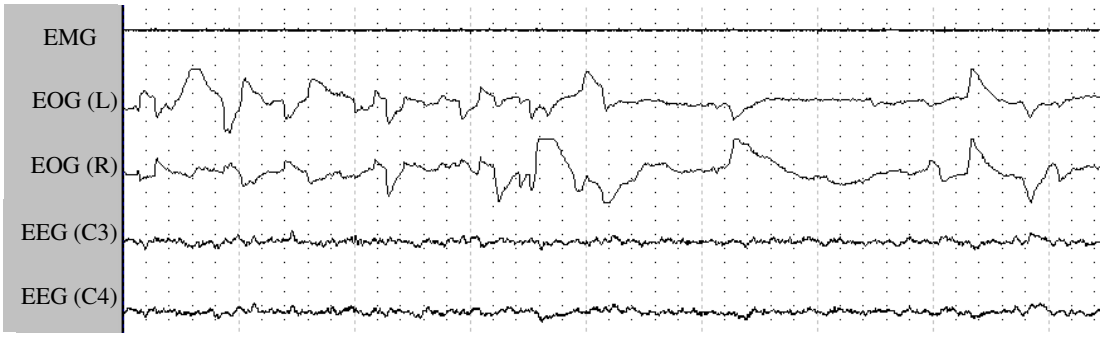

Figure 6. *An example of the desynchronised EEG, suppressed EMG and bursts of rapid eye movements in the EOG that characteristically occur during REM sleep.*

2.4 Polysomnography

Polysomnography (PSG) is the term given to the measurement and assessment of human sleep using electrophysiological techniques. The main measures that are required for sleep to be scored into stages are the EEG, the EOG, and the submental electromyogram (EMG). In addition to these three main measures, electrocardiogram (ECG), respiration, sleeping position, oxygen saturation (SaO_2), and leg movements are also usually monitored, particularly in clinical settings diagnosing breathing-related sleep disorders or as exclusion measures in research studies.

2.4.1 The Electroencephalogram

Electroencephalography is the neurophysiologic technique used to measure the electrical activity of the brain by placing electrodes on the scalp. The resultant EEG trace is produced by recording the electrical potential between pairs of electrodes, and several pairs of electrodes form what is called a montage. Different EEG montages are used depending on the reason for recording and the number of EEG channels available for recording.

The EEG is the main measure of PSG recordings and is the measure used to distinguish the individual sleep stages. Electrodes are placed on the scalp according to the International 10-20 system (Jasper, 1958 - see Figure 4), with the most common electrode placements for sleep measurement being C3 (left central) and/or C4 (right central), usually referenced to the contralateral mastoid or earlobe.

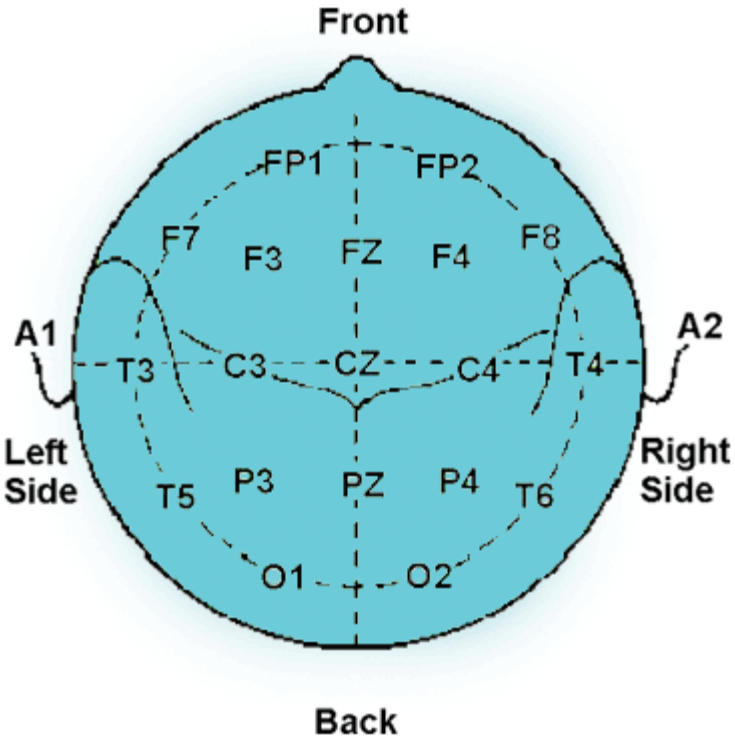

Figure 7. *Topographical view of electrode placements in the International 10-20 System. The 10-20 system is based on the relationship between the location of an electrode and the underlying area of cerebral cortex, with each site having a letter to identify the lobe and a number to identify the hemisphere location. The 10 and 20 referring to the interelectrode distances of 10% and 20% respectively.*
(Source: http://www.brainmaster.com/generalinfo/1020/1020.html).

2.4.2 The Electrooculogram

The main purpose of the EOG in PSG recordings is to record the bursts of rapid eye movements that occur during the REM sleep stage, however, the EOG is also useful in detecting the onset of sleep, which is usually marked by slow rolling eye movements. Electrodes are usually placed on the left outer canthus (LOC) and the right outer canthus (ROC) and are generally recorded using either the same reference in the supraorbital region (for example, a single electrode placed on the middle of the forehead) or to

electrodes placed in both the supraorbital and infraorbital regions for each EOG electrode.

2.4.3 The Electromyogram

The EMG measures the electrical potential that is generated by muscle cells when they contract. The main purpose of the EMG in PSG recordings is to measure the muscle tone at the mentalis/submentalis muscle region, which is primarily used for staging REM sleep, where muscle tone is suppressed. In general, two or three electrodes are placed beneath the chin or at other offset locations to the side of the chin, with three electrodes generally used for when a back-up is required.

2.4.4 The Electromyogram

The electrocardiogram (ECG) records the electrical activity of the heart and is mainly used in PSG recordings to measure the rate and regularity of heartbeats. In general, the number of leads used during PSG recordings is much less than the number used for cardiac diagnostic purposes, with as few as 2 to 5 leads commonly used during sleep recordings.

2.4.5 Additional PSG Measures

In a standard PSG recording, airflow, respiratory effort, arterial oxygen saturation (SaO_2), body position, and leg or limb movements are also commonly monitored. Airflow, which is primarily used to detect the presence of apnoeas (a decrease or cessation in airflow for a minimum of 10 seconds) and hypopnoeas (a 30% or greater reduction in airflow that is also associated with a 3% - 4% decrease in oxygen saturation or an EEG arousal), is monitored in a number of ways, with the most common detection methods being the use of nasal airway pressure and/or thermistors. A thermistor is a

thermally sensitive resistor which measures temperature change. It is placed in front of the nose or mouth to detect expiration, as there is a large difference between the temperature of air going into the respiratory system and air coming out of the respiratory system. Nasal airway pressure is also used to estimate airflow and is a more sensitive measure than the thermistor. A cessation or near cessation in airflow is seen when the recorded pressure trace shows a plateau during inspiration, or during an unsuccessful attempt to draw air into the lungs.

Respiratory effort is most commonly assessed by measuring rib cage and abdominal movement during sleep. It is an important measure for monitoring sleep-related breathing disorders, particularly in relation to respiratory effort-related arousals (RERA), which are defined as a sequence of breaths that increase in respiratory effort and lead to an arousal from sleep but do not meet the criteria for an apnoea or hypopnoea (Kryger et al., 2005).

Oxygen desaturation is a major clinical consequence of sleep-related breathing disorders. Arterial oxygen saturation (SaO_2) is standardly monitored during PSG studies using pulse oximetry, which determines SaO_2 by transmitting light into the vascular bed. The light is scattered, absorbed, and reflected, with the light that returns to the receiver being measured.

Additionally, body position or posture is often monitored, as different body positions can be related to changes in the severity of sleep disordered breathing symptoms, and limb movements are often monitored for the presence of periodic limb movements during sleep (PLMs), such as is seen in restless legs syndrome.

2.5 Sleep Physiology & Neurology

Although sleep may have originally been thought of as simply being the absence of wakefulness, it is now clear that there are distinct physiological changes between the states of wakefulness and sleep, and also between the various stages of sleep. The transition from wakefulness to sleep is typically associated with a number of physiologic changes, including the closing of eyes and becoming less responsive to external sensory stimuli (Harris, 2005). Additionally, changes in respiration, heart rate, thermoregulation, and cerebral blood flow are also evident.

2.5.1 NREM & REM Sleep Physiology

In NREM sleep, sympathetic nerve activity is low and relatively stable. Physiologic functions controlled by autonomic activity are also relatively stable during NREM sleep, with the tendency towards reduced activity during SWS. In particular, heart rate, cardiac output, brain temperature, and cerebral blood flow are all reduced during NREM sleep. Respiration also becomes more regular and there is a reduction in tidal volume, or the amount of air breathed in and out during respiration. Additionally, the level of thermoregulatory control is altered, with a decline in metabolic rate and decrease in core body temperature evident at sleep onset and during the NREM sleep state.

In contrast, REM sleep is characterised by a number of different physiologic changes distinct from those found in both NREM sleep and wakefulness. Aside from rapid eye movements, which are the most distinguishing feature of REM sleep, parasympathetic tone increases and sympathetic activity becomes more variable, leading to surges in cardiac activity and heart rate (Harris, 2005; Kryger et al., 2005). Respiration also becomes irregular and fluctuations in tidal volume are introduced. Cerebral blood flow and brain temperature increase to levels similar to those in wakefulness, and

thermoregulation is inhibited and body temperature moves towards room temperature.

2.5.2 The Role of Neurotransmitters in Sleep

Neurotransmitters, which are chemicals used to relay, amplify and attenuate electrical signals between neurons, are also involved in the initiation and maintenance of sleep and wakefulness.

Catecholamines, namely norepinephrine and dopamine, have been shown to play a role in arousal and maintaining wakefulness. If levels of norepinephrine are increased, cortical EEG activity is stimulated, which is known to promote wakefulness and also inhibit REM sleep (Rosenzweig et al., 1999; Harris, 2005; Kryger et al., 2005). Increases in dopamine are also important in promoting wakefulness, and even though dopamine neurons do not show obvious changes in firing patterns across the sleep wake cycle, extracellular levels of dopamine are known to be elevated during waking (Feenstra et al., 2000; Espana and Scammell, 2004), and sleepiness is also a common symptom of a reduction or deficiency in dopamine levels, such as is seen in Parkinson's disease (Brodsky et al., 2003; Paus et al., 2003; Roth et al., 2003; Espana and Scammell, 2004).

Acetylcholine activity is also associated with wakefulness, when cholinergic neurons fire rapidly and concentrations are at their highest, and is known to be important for vigilance and cortical activation (Kryger et al., 2005). Levels of acetylcholine decrease throughout the progression of NREM sleep stages, with increases seen at the initiation of REM sleep and also during the REM sleep state (Harris, 2005).

The neurotransmitters glutamate and histamine also promote wakefulness, with antihistamines (which block histamine activity) having the commonly known side effect of drowsiness, and glutamate is one of the major excitatory

neurotransmitters in the brain which is commonly released in association with cortical activation of spontaneous wakefulness (Kryger et al., 2005).

There is also evidence that gamma-aminobutyric acid (GABA), the main inhibitory neurotransmitter found in the central nervous system, plays a major role in sleep regulation (Lancel, 1999). This is demonstrated by the effect that GABA(A) receptor agonists have on the sleep-wake cycle. For example, the benzodiazepines zolpidem, and zopiclone, which are commonly used to treat insomnia, cause a decrease in sleep onset latency, increase SWS, and inhibit REM sleep (Steiger, 2007). These drugs also exert effects on characteristics of the EEG by promoting sleep spindles during NREM sleep (Lancel and Steiger, 1999). Recent synthetic GABA(A) agonists, namely gaboxadol and tiagabine, have also been shown to promote SWS and decrease wakefulness, however, they differ from other GABA(A) agonists as they do not affect, or only minimally affect, REM sleep (Steiger, 2007).

2.6 Sleep and Melatonin

Melatonin (N-acetyl-5-methoxytryptamine) was first identified and characterised by Aaron Lerner in 1958 (Lerner et al., 1958), when researching the presence of a skin-lightening hormone in the pineal gland. It is now known that melatonin has a much more fundamental role in the regulation of human biological rhythms, particularly in relation to the sleep-wake cycle. In addition to this role in the regulation of the biological clock, melatonin has recently been implicated as a powerful antioxidant (Reiter, 1998; Pappolla et al., 2000; Reiter et al., 2000), and there is also evidence that melatonin has an influence on the cardiovascular system (for review see Altun and Ugur-Altun, 2007) and an involvement in immune system functioning (Maestroni, 1993; Guerrero and Reiter, 2002).

2.6.1 Melatonin Synthesis and Secretion

Melatonin is primarily synthesized and secreted by the pineal gland, a tiny pea-sized endocrine structure located in the centre of the brain in the dorsal posterior segment of the diencephalon (a segment in the middle of the brain that also contains the thalamus and the hypothalamus – see Figure 8).

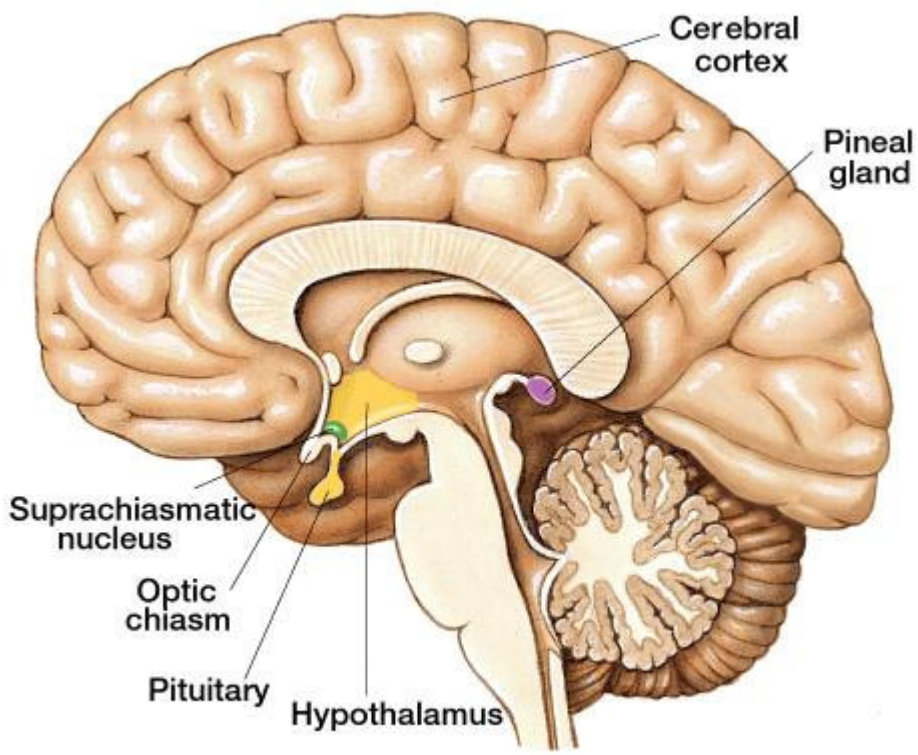

Figure 8. *Diagram of the human brain indicating the location of the pineal gland and hypothalamus.*
(Source: http://history.wisc.edu/sommerville/351/351-19.htm).

Melatonin is synthesized from tryptophan, which is taken up from the circulation and converted to serotonin, which, via a two-step process, is then converted to melatonin (Claustrat et al., 2005): shown in Figure 9.

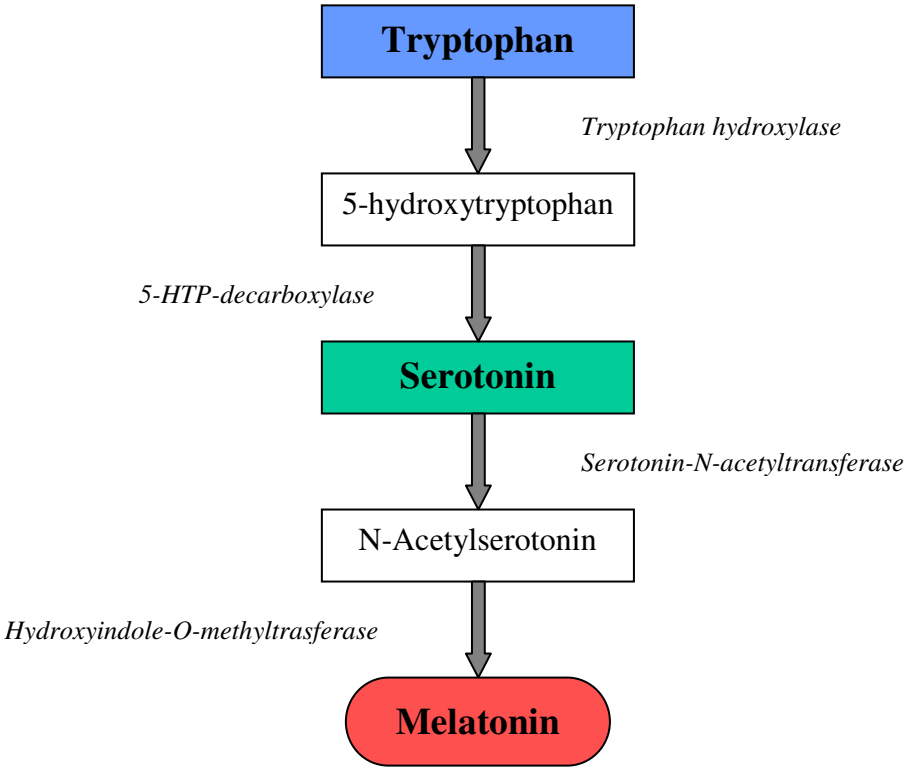

Figure 9. *Schematic representation of the steps involved in the synthesis of melatonin from its pre-cursor, tryptophan (Adapted from, Barrenetxe et al., 2004).*

The synthesis and the subsequent secretion of melatonin is highly regulated by the daily alternation of light and darkness, with plasma melatonin levels being high at night and low or undetectable during the day (Macchi and Bruce, 2004). This light-dark cycle is the main regulator of melatonin synthesis, which is evidenced by the substantial suppression that exposure to light during the night has on melatonin production (Macchi and Bruce, 2004; Claustrat et al., 2005). The normal pattern of melatonin concentrations and secretion in healthy adults is a rise that begins in the evening, with maximum levels occurring around 3.00am – 4.00am, and then levels begin

decreasing until around the end of the sleep period in the morning. The circadian (or 24-hour cycle) rhythm of melatonin activity is driven by the circadian pacemaker located in the suprachiasmatic nucleus (SCN), which receives information from the retina about the light-dark cycle and relays this information to the pineal gland to modulate the production of melatonin. This circadian synthesis of melatonin is also endogenously controlled, as compared with diel rhythms which refer to daily rhythms that are not necessarily endogenously controlled. That is, in the absence of light and all environmental cues, this endogenous pattern of melatonin production persists (Arendt, 2006).

2.6.2 Melatonin and the sleep-wake cycle

Endogenous melatonin secretion, which can be measured in plasma, saliva, or estimated in urine from its primary metabolite, 6-sulphatoxymelatonin (aMT6s), has long been associated with sleep and the sleep-wake cycle. However, although the timing of human sleep propensity is closely related to the timing of melatonin secretion, it is still relatively unclear to what extent melatonin plays a role in human sleep regulation, and what the importance of this role is (Arendt, 2006). Despite the uncertainty of the nature of melatonin's influence on sleep regulation, recent evidence suggests that exogenous melatonin, particularly when administered during the day while endogenous levels are low, appears to promote sleep (Lavie, 1997; Stone et al., 2000; Rajaratnam et al., 2003) and influence characteristics of the sleep EEG (Dijk and Czeisler, 1995; Rajaratnam et al., 2003; Rajaratnam et al., 2004). One particularly robust study recently investigated the effects of chronic melatonin administration on sleep timing, showing that exogenous melatonin exerts both direct and circadian (or phase-shifting) influences on sleep and can advance the timing of human sleep, but does not change the overall sleep profile in relation to total sleep time or the duration of NREM or REM sleep (Rajaratnam et al., 2004). The authors interpreted these results as indicating that melatonin has a sleep-facilitating effect rather than a sleep-

inducing effect (that is, melatonin administration can advance the timing of sleep and facilitate sleep without significantly affecting sleep duration) such as is seen in the common hypnotic drugs previously mentioned (see section 2.5.2). In addition to the effects on sleep timing, sleep spindle activity was also increased in the first half of sleep following melatonin administration, which supports previous research that has suggested an association between melatonin and the circadian regulation of sleep spindle activity (Dijk and von Schantz, 2005). Overall, these and other previous findings suggest that endogenous melatonin does in fact play a role in the circadian regulation of sleep propensity, although the mechanisms of this melatonin-induced alteration in sleep and circadian timing remains unknown and is perhaps a direction for future research.

2.7 Functions of Sleep

Although we know that human sleep is much more than simply the absence of activity or consciousness, the functions of sleep remain largely unclear. This section considers and discusses the main theories of sleep function in humans.

2.7.1 Restorative Theory of Sleep Function

The restorative theory was one of the earliest proposed theories of sleep function, and is based on the hypothesis that sleep serves to restore or replenish physiological and biochemical processes that are used or depleted during wakefulness. In support of this hypothesis the release of growth hormones, which stimulate growth and cell reproduction, occurs during the NREM sleep phase (Steiger, 2007). However, in general there is little evidence to support the restorative theory of sleep function (Kryger et al., 2005). Additionally, this theory cannot readily explain the significant variations in the daily sleep quotas among mammalian species, which range

from approximately 3 hours for animals such as horses and elephants, to 19 hours for bats, with humans lying roughly in the middle with an average total daily sleep time of 8 hours (Kryger et al., 2005).

2.7.2 Energy Conservation Theory of Sleep Function

A second theory of sleep function is that mammalian sleep is for energy conservation. This hypothesis is based on a number of physiological changes that occur during sleep (see section 2.5.1), such as lowered heart rate, blood pressure, and slower respiration, but particularly highlights the reductions in metabolism and body temperature during sleep as the main factors in energy conservation. This theory is supported by the fact that, in general, small animals have a higher metabolic rate than larger animals, and therefore they tend to sleep longer than larger animals in compensation for the higher energy expenditure in metabolic activity (Rosenzweig et al., 1999). However, although there is some degree of support for energy conservation as a function of sleep, this theory does not explain the continuous movement that occurs during sleep in such species as the dolphin (Kryger et al., 2005), and suggest that energy conservation may only be one aspect of the function of sleep.

2.7.3 Protection and Preservation Theory of Sleep Function

This theory of sleep function is based on the idea that sleep evolved as a type of defence mechanism to protect individuals during the part of the day that is most dangerous to them. This adaptive role of sleep suggests that organisms sleep at times when they are vulnerable to predation or other dangers, therefore maximising their safety by avoiding potential prey (Meddis, 1975). However, although this theory may seem reasonable, it would also be just as plausible for an organism to be awake and extremely alert at the time of the day when danger is heightened, as being asleep or in a state of reduced awareness would decrease sensitivity to external stimuli

and possibly increase an organisms' vulnerability to predation. It also does not account for those species that sleep with one hemisphere constantly active for survival reasons other than predator avoidance (Kryger et al., 2005).

2.7.4 Cognitive and Behavioural Benefits of Sleep Function

More recently, theories of sleep function have focussed on the possible cognitive and behavioural benefits of sleep, particularly in relation to learning and memory. Numerous studies have supported the notion of sleep-dependent memory processing, particularly the consolidation of procedural memories (that is, memory for actions and skills) during stages of NREM sleep (Huber et al., 2004; for review see Walker and Stickgold, 2006). There is also some recent evidence that suggests that sleep may play a role in the consolidation of declarative memory (that is, memory for facts and experiences), and that it helps to protect these memories from subsequent associative interferences (Ellenbogen et al., 2006). Although the mechanisms behind a relationship between sleep and cognitive abilities remains largely unknown, there is growing evidence to suggest that sleep spindle activity in the EEG during NREM sleep is correlated with visuospatial memory retention and also more general cognitive and memory-related abilities (Schabus et al., 2004; Clemens et al., 2005; Clemens et al., 2006; Schabus et al., 2006). However, while there is some evidence to suggest that sleep plays a role in learning and memory consolidation, there are also some inconsistencies in the literature that would suggest that this is not the case. For example, Vertes and Segel (2005) dispute the notion that sleep plays a role in declarative memory consolidation and also highlight the point that numerous studies have failed to find an association between sleep and the consolidation or enhancement of sensory or motor skills. The authors also suggest that other explanations for improvements following sleep would be more likely, such as the lack of interference or distractions during sleep, which is supported by one recent study that showed no difference between

improvements regardless of whether individuals were tested following sleep or simply restful waking (Gottselig et al., 2004).

2.8 Summary

Sleep is a dynamic and complex process that involves a number of changes in physiological and cerebral activity. It is normally classified into two distinct phases, NREM and REM sleep, and is assessed using polysomnography. The sleep-wake cycle follows a 24-hour circadian rhythm, of which the hormone melatonin is believed to play a role. The function of sleep is a complex issue that remains largely unknown, however, it is likely that the reason for sleep is not simply to serve one function, but rather to serve a number of roles important for everyday life.

Chapter 3: Electromagnetic Fields and Mobile Phones

This chapter provides an introduction to the characteristics of electromagnetic fields, specifically the non-ionising radiofrequency radiation that is associated with mobile phones. A detailed description of the Global System for Mobile Communications (GSM) network and the way in which mobile phones transmit is also provided. This is followed by a description of the specific absorption rate (SAR) of radiofrequency radiation in biological tissue and the computational and experimental techniques used for measuring this absorption. A brief description of national and international radiofrequency safety guidelines in relation to GSM mobile phones concludes the chapter.

3.1 Electromagnetic Fields

Electromagnetic fields (EMF) are composed of two different vector fields – the electric, or 'E-field', and the magnetic, or 'H-field'. Electric fields exist whenever electric charges are present. They are produced by positive or negative charges that exert a force on other charged objects in the field and are measured in volts per metre (v/m). E-fields are strongest at distances close to the device (such as a mobile phone) in use and diminish as distance from the device increases (Habash, 2002). They can be shielded or weakened by conductors placed in the field, or objects such as buildings or the human body (Habash, 2002). Magnetic fields are produced by the motion of electric charges, which exert force on other moving charges, and the field intensities are measured in amperes per metre (A/m). The magnitude of the magnetic field per unit area is known as the magnetic flux density and is measured in Tesla (T). Like E-fields, magnetic fields are generally strongest near the source and diminish as distance increases

(Habash, 2002). However, unlike E-fields, which exist even when there is no current flowing, magnetic fields are only produced when current flows (i.e. when a device is turned on), and they can also easily penetrate buildings and the human body as they are not shielded by most common materials (Habash, 2002).

The power of an electromagnetic wave, or the rate at which energy is consumed or produced, is usually measured in Watts (W), where one watt is equal to one joule (the SI unit of energy) per second (J/s). The intensity, or power density (also referred to as power flux density), is defined as the amount or distribution of power passing through an area, and is most commonly expressed or measured in Watts per square metre (W/m^2) (Habash, 2002).

Electromagnetic radiation can be classified into different ranges, which are distinguished by the frequency and wavelength of the electromagnetic waves. When these electromagnetic waves are arranged in a continuum they form what is known as the electromagnetic spectrum, which ranges from radio waves at low frequency to X-rays and gamma rays at much higher frequencies (Figure 10). The frequency of an electromagnetic wave is the rate of oscillation of the wave and is measured in Hertz (Hz), which means the number of oscillations or cycles per second, and can be used to describe any period event, such as the ticking of a clock or the beat of the human heart. The wavelength of electromagnetic waves is defined as the distance between repeating sections of the wave (i.e. the distance from one wavecrest to the next) and is commonly denoted by the Greek letter lambda (λ). Frequency and wavelength are inversely related (wavelength (λ) = Speed of light/Frequency), therefore as the frequency becomes larger the wavelength shortens, and vice versa.

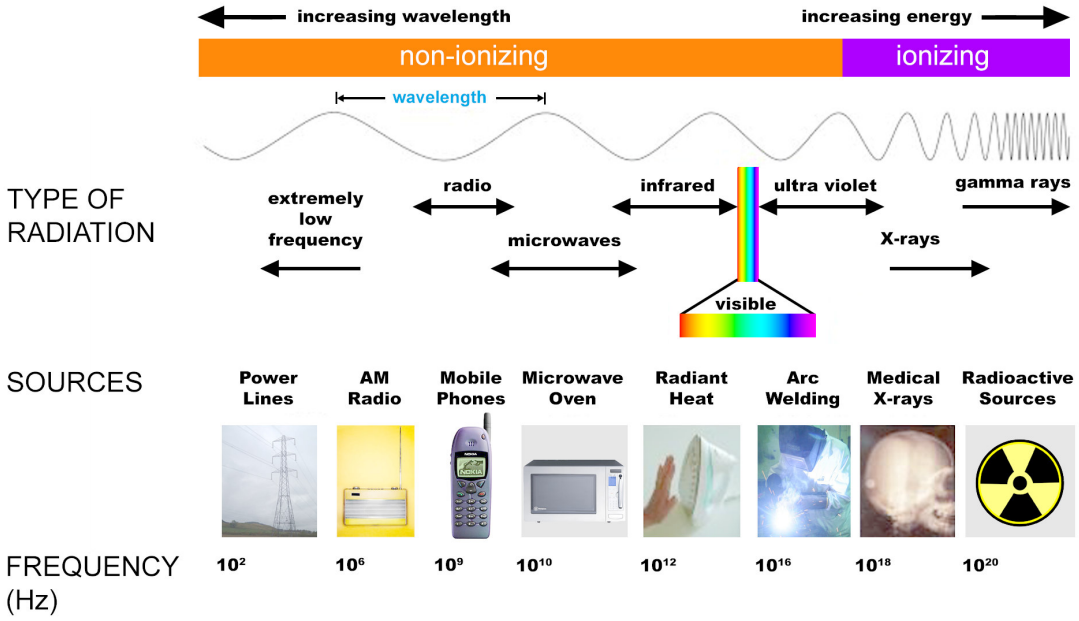

Figure 10. *The electromagnetic spectrum (adapted from ARPANSA,* http://www.arpansa.gov.au/basics/ion_nonion.htm).

3.2 Ionising and non-ionising radiation

Based on frequency, the electromagnetic spectrum is also divided into two distinct sections, classified as ionising and non-ionising radiation (Figure 10). Ionising radiation is radiation that has enough energy to remove electrons from an atom, creating what are known as free radicals (atoms with unpaired electrons that are usually highly reactive) in living matter and subsequently increasing the risk of chromosomal damage or damage to biological tissue (Habash, 2002; ARPANSA, 2003). X-rays and gamma rays are both classified as ionising radiation and both have the ability to penetrate biological tissue and potentially cause damage. However, this can also be beneficial as ionising radiation is now commonly used in medicine for its ability to kill living cells, particularly in the treatment of malignant cancers by targeting and killing the cancerous cells (Habash, 2002).

Non-ionising radiation refers to radiation that does not have sufficient energy to cause ionisation or remove an electron from an atom. In regards to bioelectromagnetics research, the two most relevant frequency ranges that lie in the non-ionising section of the electromagnetic spectrum are extremely low-frequency (ELF) and radiofrequency (RF) radiation. ELF radiation refers to electromagnetic fields below 3 kHz, and common sources of ELF radiation are power lines, household appliances, and computers.

The other main type of non-ionising radiation, radiofrequency (RF) radiation, refers to those fields in the electromagnetic spectrum that lie between 3 kilohertz (kHz) and 300 gigahertz (GHz). RF radiation is present in our everyday environment and common sources include appliances such as AM and FM radio, television, microwave ovens, and also medical applications such as magnetic resonance imaging (MRI). Currently the main use of radio waves in society is for communication purposes, including radar and satellite, with perhaps the most prolific use to date being the introduction of mobile phone technology.

3.3 Mobile Phone Networks

Mobile phones transmit and receive signals using RF electromagnetic energy (EME), also commonly referred to as radio waves. Currently in Australia there are three main mobile phone networks operating which can be defined by the frequency bands at which they transmit: CDMA (Code Division Multiple Access), which transmits at around 800 MHz; UMTS (Universal Mobile Telecommunications System), also more commonly known as 3G, which transmits at 2100 MHz; and GSM (Global System for Mobile Communication), which transmits at either 900 MHz or 1800 MHz (ARPANSA, 2006). The GSM network is the fastest growing communication technology to date, with over 2 billion users worldwide (GSMWorld, 2006). The majority of research concerning mobile phone technology has therefore

focussed on digital GSM networks, and given that GSM technology accounts for more than 80 per cent of mobile phone connections globally, the following sections will only refer to technology and transmissions associated with digital GSM mobile phones.

3.4 GSM Mobile Phone Characteristics

GSM mobile phone networks were first introduced in Finland in 1991 to replace the original first generation (1G) or analogue phone networks that were in use during the 1980's (GSMWorld, 2006). GSM mobile phones work by communicating with a base station, which is a fixed station or tower that has a set of transmitting and receiving antennas that communicate with the mobile phone. Base stations are generally located at heights between 10 and 75 metres, typically on top of towers, water tanks, but also on rooftops or attached to the sides of buildings. The height of base station antennas is an important factor as they must be both high enough to ensure that signal coverage is adequate, and also not placed so high that interference with remote cells occurs (Habash, 2002).

GSM mobile phones transmit and communicate with the base station using a technique called Time Division Multiple Access (TDMA). The advantage of this system is that a number of users can communicate at the same time using a single channel or cell, as each cell is divided into 8 slots with each user allocated a different time slot (Pedersen and Andersen, 1999). This is achieved by transmissions from the handset occurring as a burst of power that lasts for 0.577ms, which is transmitted every 4.6ms. This pulsing pattern results in a repetition rate (or pulse modulation) of the signal at a frequency of 217 Hz and also means that the average RF power output of the mobile phone is generally much less than the output power within each pulse, which is referred to as the peak power (NRPB, 2003). These pulse modulation patterns in transmission are repeated for each of the 8 time slots in a cell and

form what is called a frame. The GSM network is based on a timed multiframe that consists of 26 frames lasting for a duration of 120ms, with the first 25 frames transmitting and the 26th frame remaining idle or inactive (Pedersen and Andersen, 1999). The absence of transmission at the 26th frame leads to apparent pulsing of the signal at 8.34 Hz (i.e. 217 Hz / 26), which is a permanent feature of the output that is unaffected by call density, or the number of calls being transmitted by each cell (Hyland, 2000).

GSM mobile phone systems also have two other features, discontinuous transmission (DTX) and adaptive power control (APC), which alter the power output of the handset and lead to additional low frequency components in the signal transmitted. DTX in GSM mobile phones means that transmission of information is only sent while the user is talking, although the connection is still maintained (Pedersen and Andersen, 1999). Although it was primarily designed to save battery power while the phone is being used, it also results in a reduction of exposure by a factor of 2, assuming that only one person is speaking at a time and that both speakers contribute equally to the conversation (Pedersen and Andersen, 1999; NRPB, 2003). The second feature of GSM mobile phones, APC, is a function of the system that permits the power being transmitted by the handset to continually change according to the amount of power required to maintain the connection (Pedersen and Andersen, 1999). APC is accomplished by the handset continually sending transmission information to the base station, which subsequently decides whether power needs to be increased or decreased in order to keep the connection and relays this information back to the handset, which changes power accordingly. This function ensures that power output throughout a conversation is kept to the minimum required, whilst maintaining the quality of the connection and minimising interference (Pedersen and Andersen, 1999).

3.5 Dosimetry and Specific Absorption Rate

When using a mobile phone some of the power emitted by the handset is absorbed by the body, in particular the head, as the handsets' antenna is generally closest to the head during normal use. Dosimetry refers to the evaluation of the amount of absorption of EMF in biological tissue following exposure to sources such as mobile phones, based on the electric field strength, induced current density, and the rate of energy absorption (NRPB, 2003). The most commonly used quantity to describe the absorption of RF radiation from mobile phones is known as the specific absorption rate (SAR), which is defined as the rate at which energy is absorbed by a particular mass of tissue (IEGMP, 2000; NRPB, 2003). SAR, which is expressed in watts per kilogram, is calculated using the formula $\sigma E^2/p$, where σ is the electrical conductivity of the particular tissue in question, p is the tissue density, and E is the rms (root mean square) value of the electric field strength in a particular location in the biological tissue (IEGMP, 2000; NRPB, 2003). There are two types of SAR commonly referred to in bioelectromagnetics research, known as whole-body average SAR and localised (partial-body) SAR, which are differentially applied depending on the circumstances and the source with which exposure is being evaluated. Whole-body SAR refers to the total amount of energy that is transferred to the body per unit time, divided by the total body mass, whereas localised SAR refers to the total amount of power absorbed within a defined unit of mass or smaller section of the body (Habash, 2002). Localised SAR is particularly important for determining exposures from small sources, such as mobile phones, which primarily affect only a small region of the body. The SAR from exposure to a mobile phone varies widely depending on the model and design of the handset (for example, whether it has an external or internal antenna configuration) and changes in position during use (such as distance between the handset and the users head), and differences in tissue composition and conductivity will also lead to modifications in the SAR measured from RF sources (Christ and Kuster, 2005).

3.5.1 Computational Techniques for Estimating SAR

The two most common methods of estimating the SAR from GSM mobile phones are via computational and experimental techniques. Computational methods generally involve the use of analytical and/or numerical techniques, with a combination of techniques often useful in providing a more complete calculation of SAR (Habash, 2002). Analytical techniques involve calculating the power absorption of incident fields in biological models of the human body or parts of the human body that are relevant to the exposure source (such as head when determining SAR from mobile phones). A number of different models that vary in shape, size and complexity can be used to analytically estimate SAR, and the choice of model usually depends on a number of factors, such as the frequency of the source, the aim of the calculations, and whether the whole body or localised exposure is to be investigated (Habash, 2002). With regard to numerical techniques for estimating SAR a number of methods have been developed, and the three main methods generally used for determining SAR from exposure to mobile phones are the *method of moments* (MOM), the *finite element method* (FEM), and the *finite-difference time domain* (FDTD). The MOM is a boundary element method that involves the model being broken down into virtual wires and/or metal plates, with the wires subdivided into segments and the metal plates subdivided into surface patches, both of which must be smaller than the wavelength of the device under investigation (Habash, 2002). A virtual source of current is then applied and the current on every wire segment and surface patch is determined, which allows the electric field at any point in space to be calculated. The main disadvantage of using the MOM is that computational requirements are large, making it less efficient than volume-discretisation methods, such as FDTD and FEM. The advantage of FEM models, which were originally designed for structural analysis problems, is that they require the complete volume of the configuration, rather than just the surface, to be meshed, with each mesh element able to have different properties where appropriate (such as biological tissue in the human body). However, this is also a drawback of the FEM because it is

very difficult to integrate the mesh elements when investigating complicated structures (Habash, 2002). The other volume-discretisation method, FDTD, is specifically an electromagnetic modelling method based on Maxwell's equations, and is currently the most popular method used for estimating SAR (Habash, 2002). FDTD is a time-domain technique that alternately calculates the electric and magnetic fields in the defined region of a simulation, with the ability for different materials to be modelled within the computational domain. The advantages of using FDTD are its versatility (it is easy to understand and implement in software), and the analysis of a system covering a wide range of frequencies can be performed with a single simulation (Habash, 2002).

3.5.2 Experimental Techniques for Estimating SAR

Experimental techniques for estimating SAR are useful in both confirming results obtained from computational methods, as well as being able to provide SAR measurements where computational methods are inadequate or are unable to be performed. Due to the difficulties of measuring the SAR inside the human body, the most common method for estimating SAR is to measure either the induced E-field or temperature rise inside a phantom that is usually shaped as a representation of the human body (or the human head in the case of SAR measurements applicable to mobile phone exposures). These phantoms are filled with various types of tissue-simulating liquid, to represent the dielectric properties of the tissue under investigation, and then measurements are made inside the phantom. For mobile phone SAR evaluations, measuring temperature rise is quite difficult due to the extremely small temperature changes associated with mobile phone exposure, and therefore, the most common and convenient way of measuring SAR is to use an E-field probe to measure the electric field strength inside the phantom (Zombolas, 2003). For SAR measurements from mobile phone exposure the probe is usually attached to a high precision robotic arm and moved from point to point through the tissue simulating liquid in the phantom, with the

mobile phone placed in a position on the outside of the phantom that simulates normal use (Figure 11). From these measurements, the average SAR and the peak SAR value and position are determined for the specific mobile phone under investigation.

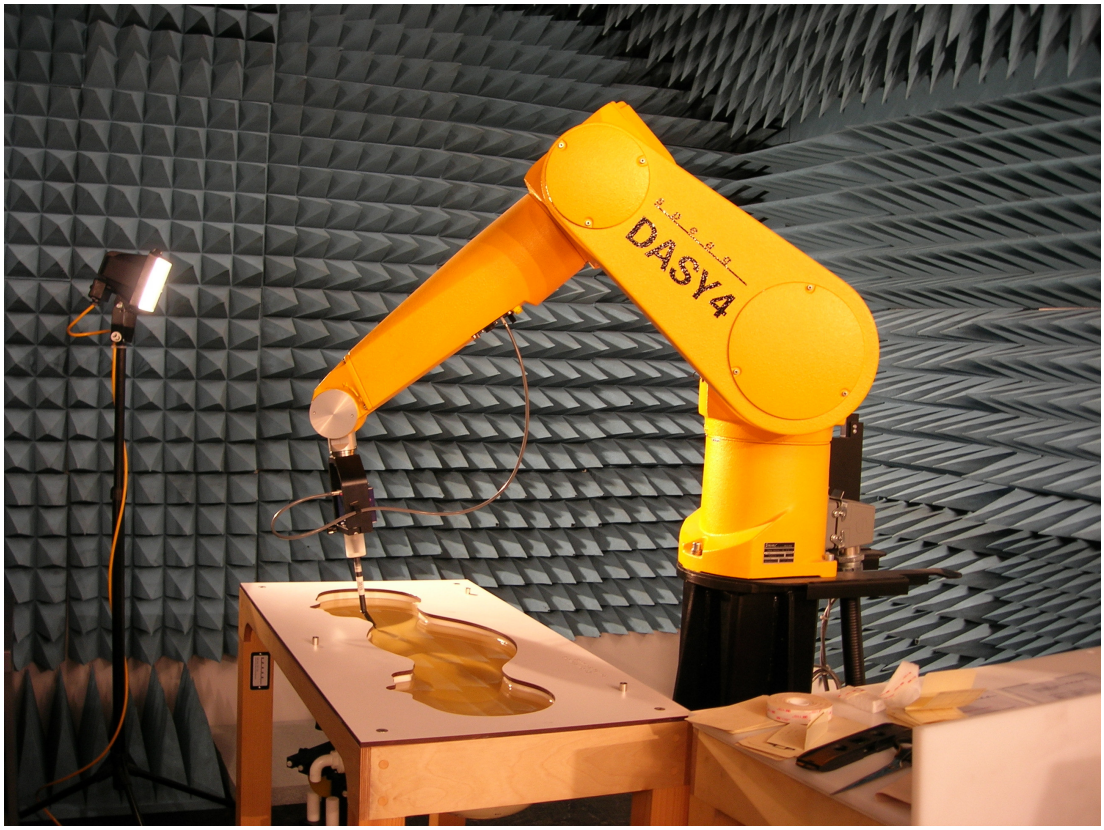

Figure 11. *Evaluation of SAR using the flat Phantom.*

There are a number of different head and body phantoms that can be used for measuring SAR, however, due to most countries requiring testing of mobile phones and other electronic devices for compliance with RF radiation safety standards (see section 3.6), the phantom that is now accepted worldwide for RF safety compliance testing of mobile phones is the Specific

Anthropomorphic Mannequin (SAM) (Beard and Kainz, 2004). The SAM phantom was developed by the Institute of Electrical and Electronics Engineers, Inc (IEEE) based on data of surveyed adult male heads and was designed in order to give a conservative measure of SAR for the majority of users (Gordon et al., 1989). The conservativeness of the SAM phantom has been independently confirmed and has also been shown to be comparable with numerical evaluations of the SAR from mobile phone radiation (Christ et al., 2005; Kainz et al., 2005)

3.6 RF Radiation Safety Guidelines

Due to the significant growth of mobile telecommunications and other devices operating within the RF range, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) developed a set of guidelines in 1998, based on an extensive review of the scientific literature, for limiting exposure to EMF in order to provide protection against the known adverse effects of EMF exposure (ICNIRP, 1998). For all devices in the 10 kHz to 10 GHz frequency range, which includes GSM mobile phones, the ICNIRP guidelines recommend a limit of 2 W/kg for localised SAR at the head and trunk in order to prevent excessive localised tissue heating, or heating in excess of 1°C (ICNIRP, 1998). This limit refers to public exposures, which are more restricted (by a factor of 5) than the recommended occupational exposure limits. More recently, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) developed a set of guidelines detailing maximum exposure levels for RF fields between 3 Hz and 300 GHz that prevent adverse health effects occurring (ARPANSA, 2003). For the range encompassing GSM mobile phones (100 kHz to 6 GHz), the ARPANSA exposure limit was also set at 2 W/kg, which is consistent with the ICNIRP recommendations. Currently the ARPANSA standard is the one used to set limits in Australia, however, it does not deviate from the original ICNIRP guidelines as there was no scientific justification from ARPANSA's review of

the updated literature to suggest that the ICNIRP guidelines were not adequate for health protection (ARPANSA, 2003). Although the World Health Organisation (WHO) strongly promotes the harmonisation or use of one international standard, there are still some countries with national exposure limits that vary widely from the ICNIRP guidelines, which, according to the WHO, can lead to an increase in confusion for advisory and regulatory boards, as well as increases in public anxiety (WHO, 2006). With the concern of adverse health effects from mobile telecommunications already high, particularly in Australia, the implementation of a unified international standard may assist in reducing confusion and concern, particularly where there is substantial scientific evidence to support the exposure limits that are recommended.

Chapter 4: Mobile Phones and Health

This chapter provides an introduction to the field of bioelectromagnetics research and includes a review of previous research regarding mobile phones and health effects in humans. In context with the current study, the review of mobile phone-related health effects specifically concentrates on those studies related to the human brain and/or head region, namely research concerning brain tumours, human cognition, the electroencephalogram, and effects on regional cerebral blood flow.

4.1 Introduction

Bioelectromagnetics is a vast and rapidly growing research discipline concerned with investigating and understanding the interaction of electromagnetic fields with biological systems. The rapid growth in bioelectromagnetics research is the result of the increase in the development of electromagnetic facilities and devices which are now widely used in the home and workplace. It is generally agreed that within the RF range, the mechanisms of biological effects due to exposure to RF fields can be considered as either thermal or nonthermal. Thermal effects from RF radiation refer to exposure intensities that are sufficient to cause significant heating of the biological tissue, causing rises in the core body temperature despite the thermoregulatory processes performed by the body to try and maintain constant core body temperatures (Habash, 2002). Thermal effects from RF radiation can have significant impacts on human health, particularly when induced tissue heating is increased by more than 1°C, exceeding the thermoregulatory capacity of the human body (Habash, 2002). In contrast,

nonthermal effects refer to those effects from RF radiation where there is no significant induced temperature change in the body, and therefore the thermoregulatory mechanisms are not challenged and core body temperature is maintained, despite the RF energy absorption. Consequently, the biological effects associated with such low level emissions are thought to be due to mechanisms other than those that are known to occur from significant heating of biological tissue.

Although some controversy surrounds the potential for RF radiation exposure to cause nonthermal biological effects, a large amount of bioelectromagnetics research has focussed on putative nonthermal effects, particularly those related to exposures from mobile phones, which emit low level RF fields. Research on the effects of mobile phone use and exposure to mobile phone-type RF fields has also received heightened attention in recent years due to the increase in public awareness regarding the possible health effects caused by exposure to mobile phone emissions, particularly in relation to consequences that may be associated with the absorption of energy in the head and brain regions where mobile phones are typically used. The possibility of health risks associated with mobile phone use has also become an important issue due to the rapid growth of this technology and the sheer numbers of people exposed to mobile phone RF EMF's, with over 2 billion subscribers worldwide, making this the fastest growing technology that the world has experienced (GSMWorld, 2006).

4.2 Mobile Phones and Cancer

Significant public concern regarding the possible relationship between mobile phone use and cancer incidence has risen in recent years due to a number of factors, including the unprecedented increase in levels of mobile phone use in society, as well as the large amount of media attention that this issue has received worldwide. Although the RF fields emitted by mobile phones are non-ionising and therefore unable to directly break molecular bonds (a mechanism associated with mutagenesis in biological tissue), debate regarding a causal relationship between mobile phones and cancer still remains, with the proposition that mutagenesis may be influenced indirectly by RF fields at one of the various stages in the malignant process and therefore indirectly leading to an increased risk of disease (Kundi et al., 2004). Due to this concern, a number of epidemiological studies have been conducted over the past ten years to assess the risk of mobile phone use on cancer development.

The first study to be reported was a large cohort study from the United States looking at the overall mortality among mobile phone users compared with the overall mortality in users of transportable phones, such as car or bag phones (Rothman et al., 1996). The idea behind this comparison in mortality was based on the different exposure parameters of these devices, with mobile phones having an antenna incorporated in the handset and therefore placing it in close proximity to the users head and brain region, whereas transportable phones typically had a separate transmitter, thus increasing the distance between the antenna and the users head (Rothman, 2000). Mobile phone use was classified as the length of time a person was subscribed as a mobile phone customer, and almost all participants in the cohort used analogue mobile phones. The results showed no difference in overall mortality between users of the two types of phones. An expansion on this cohort was also performed based on details of estimated average daily use data obtained from billing records, however, there was still no significant

association found between mobile phone use and mortality from brain cancer, leukaemia, or all types of cancers combined, although, it should be noted that this follow-up was unable to be fully completed due to legal reasons (Dreyer et al., 1999).

In a case-control study in Sweden, Hardell et al. (1999; 2000; 2001) examined the use of mobile phones and this risk for brain tumours using tumour cases that were identified between 1994 and 1996. A questionnaire was used to ascertain detailed information regarding mobile phone use, including a trained nurse who followed up on any answers that may have been missing or unclear. The data showed that, overall, there was no increased risk of brain tumours associated with mobile phone use, regardless of whether the phones were analogue or digital mobile phones. The authors also reported that the odds ratios for ipsilateral mobile phone use (that is, predominant mobile phone use on the same side of the head as the tumour was located) were elevated, particularly at temporal and occipital locations; however this increase did not reach significance.

A further study was also conducted by Hardell et al. (2002; 2002), using a larger study region of tumour cases identified between 1997 and 2000, resulting in a larger number of tumour cases compared to their previous study. A significantly increased risk was reported for analogue mobile phone use which showed a dose-response relationship, with higher odds ratios reported for longer tumour latency periods. No increased risk was reported for digital mobile phone use. Consistent with the authors' earlier study, increased risk for ipsilateral phone use and tumour location was also reported, which was independent of type of phone (analogue or digital) used. The main conclusion drawn from this larger study was that there was an increased risk for brain tumours among analogue mobile phone users.

Following the reports of cancer incidence in the Swedish population, two more case-control studies conducted in the United States were published

(Muscat et al., 2000; Inskip et al., 2001). Both studies used cohorts from between 1994 and 1998, with 88% of participants using analogue phones in one of the studies (Muscat et al., 2000), and although no data on phone type was obtained in the second study, it was presumed by the authors that participants would have predominantly been analogue phone users given the dates of the cohort selected (Inskip et al., 2001). The data from both studies suggested that the use of mobile phones was not associated with overall risk of brain tumours (Muscat et al., 2000; Inskip et al., 2001). There was also no association found in either of the studies between the laterality of the tumour and the side of the head where the phone was reported to be typically used.

Also reported early in 2001 were the results of a population based cohort study of cancer incidence among mobile phone users in the Danish population, based on mobile phone subscriptions between 1982 and 1995 (Johansen et al., 2001). The participants within this period used both analogue and digital GSM mobile phones, however, the duration of subscription was only available for GSM mobile phone users. The results of this nation-wide cohort study showed that there was no increased risk for leukaemia or tumours of the brain and nervous system based on mobile phone use. There was also no significant association found between cancer risk and the duration of mobile phone use, the time since first subscription, the age of users at first subscription, or the type of mobile phone (analogue or digital) used (Johansen et al., 2001).

Auvinen et al. (2002) also conducted a register-based case control study on mobile phone use and brain tumours and salivary gland cancers diagnosed in Finland in 1996. Information on mobile phone use was based on subscription records obtained from the network providers, with both analogue and digital users identified within the identified cancer cases. Overall, the authors reported no association of mobile phone use with either brain tumours or salivary gland cancers, however, there was a weak association

reported for risk of gliomas, a type of tumour that arises from glial cells and most commonly associated with the brain, and mobile phone use.

4.2.1 Methodological Limitations

The studies reviewed concerning mobile phone use and the risk of cancer suffer from a number of important methodological limitations, including insufficient or short study periods, unknown and different mobile phone type, recall error and recall bias, and the assessment of exposure.

All of the reviewed studies predominantly investigated cancer incidence during the 1990's which limits the results due to the short period of time that mobile phones had commonly been used. Therefore, all of the results to date are only relevant for estimating the possibility of cancer risk from short-term mobile phone use and are insufficient to draw conclusions regarding an association between long-term mobile phone use and cancer risk.

Another methodological issue concerns the different mobile phone types assessed in the studies, with large differences in the numbers of analogue and digital users identified. Furthermore, one study included a large number of mobile phone users in which the type of mobile phone handset used was unknown, which severely limits interpretations and comparisons with other studies.

One of the most important limitations related to case-control studies is recall bias concerning the amount of mobile phone use, and in particular, recall regarding the side of the head that the mobile phone was predominantly used. That is, respondents might be more likely to report that they predominantly used a mobile phone on the same side of their head as the tumour location based on their beliefs about mobile phone use and cancer risk, which could skew the results and inaccurately lead to a report of an association between phone use and cancer incidence or location.

Similarly, the use of subscriber lists to ascertain an individuals phone use has also been identified as a source of potential error as it provides no reliable data on individual patterns of use (Kundi et al., 2004). Therefore, studies using subscriber lists as an assessment of exposure are very limited in terms of the conclusions that are able to be drawn regarding mobile phones and cancer risk.

4.2.2 Interphone Study

Due to the inconsistent results and methodological limitations of the early research concerning the possible cancer risk associated with mobile phone use, the International Agency for Research on Cancer (IARC) initiated a multi-national series of studies, called the Interphone project, in order to assess whether mobile phone use does in fact increase the risk of cancer, or more specifically, whether the RF EMF emitted by mobile phone handsets is carcinogenic. The countries involved in the Interphone project are Australia, Canada, Denmark, Finland, France, Germany, Israel, Italy, Japan, New Zealand, Norway, Sweden, and the United Kingdom. In order to maximise the power of finding a risk if it does exist, the studies were designed to mainly focus on tumour incidence in relatively younger populations, aged between 30 and 59 years, as this age group was deemed to have had the highest prevalence of mobile phone use over the 5-10 years prior to the study commencement. It was also designed to concentrate on those regions within the participating countries that had the longest and largest amount of mobile phone users or subscriptions during the same time period.

The first interphone results to be reported were from Sweden, with a study that included 371 incident glioma cases and 273 incident meningioma cases (Lonn et al., 2005). No increased risk of glioma or meningioma was found for regular mobile phone use. There was also no increased risk seen for ipsilateral tumours, or for durations of mobile phone use that were more than

10 years. Since this study was reported, three other countries have also reported interphone results, and overall, regular phone use was not found to increase the risk of glioma (Christensen et al., 2005; Hepworth et al., 2006; Schuz et al., 2006) or of meningioma (Christensen et al., 2005; Schuz et al., 2006). However, the German interphone study (Schuz et al., 2006) reported an increased risk for glioma, but not meningioma, amongst those who had used a mobile phone for at least 10 years, and the UK interphone study found a significant increase of risk for reported phone use ipsilateral to the tumour, while a significant reduction was seen for contralateral use. This finding was explained by the authors as likely being due to recall bias.

In addition to the studies on glioma and meningioma, a combined analysis of acoustic neuroma risk in five northern European countries (Denmark, Finland, Norway, Sweden, and the UK) has also recently been reported (Schoemaker et al., 2005). The analyses included 678 acoustic neuroma cases, and results showed that regular mobile phone use did not increase the risk of acoustic neuroma. There was also no association of risk with duration of mobile phone use, lifetime cumulative hours or number of calls, or for the use of analogue or digital mobile phones considered separately. The only elevated risk reported was for reported phone use ipsilateral to the tumour in those who had used a mobile phone for 10 years or longer.

Overall, the weight of evidence from the initial interphone studies suggests that mobile phone use is not associated with an increased risk of brain tumour. However, results of further studies and the combined interphone analysis are required before any firm conclusions regarding tumour risk can be drawn.

4.2.3 Mobile Phones and Cancer – Summary

Due to mobile phones being conventionally used in close proximity to the head, concerns regarding possible detrimental effects, particularly in regards to cancer and brain tumours, have continued to arise over recent years. Although several cohort and case-control studies have been carried out to address these concerns, including the ongoing interphone study, controversy remains regarding the risk of brain tumours being associated with mobile phone use. Although some significant and some trend level associations have previously been reported, there has been little or no consistency in these reports, and given the quite substantial limitations that exist with the majority of these studies (see section 4.2.1), reported effects should be treated with caution.

Taking into consideration the recent results of the interphone study, which was designed to overcome the methodological limitations of the previous studies, the weight of evidence would suggest that there is no increased risk of brain tumours associated with mobile phone use. However, given that most studies do not go beyond 10 years of mobile phone use, the possibility of longer-term effects from mobile phone use cannot be excluded.

4.3 Mobile Phones and Brain Function

In addition to the public concern regarding mobile phones and cancer, there has also been significant concern regarding the effects that mobile phone emissions may have on human brain activity in general, particularly due to the proximity of the mobile phone to the head and brain when in normal use. This has led to a number of studies over the past ten years that have investigated the effects of mobile phones on two specific parameters: cognition and the EEG. Cognitive performance has been examined both during and following RF EMF exposure, and the specific cognitive processes that have typically been investigated include memory, attention, and

measures of reaction time. The EEG has also been examined both during and following RF EMF exposure, with investigations typically focussing on EEG power spectra and components of the EEG that reflect cognitive processing or reflect a specific neural response to a stimulus, such as event-related potentials (ERP).

4.3.1 Mobile Phones and Cognition

The first of numerous studies to investigate the effects of mobile phones on human cognitive functioning was reported by Preece et al (1999). Participants undertook 3 exposure sessions (a 915 MHz continuous wave signal, a 915 MHz signal pulse-modulated at 217 Hz, and a control/sham condition) during which their performance on a number of cognitive tasks (including reaction time, and short and long term memory processing) was measured. Each session ran for approximately 25 – 30 minutes, and there was a 48 hour wash-out period between testing sessions. Choice reaction time was found to be decreased in the continuous wave exposure condition (designed to represent an analogue-like phone signal), with none of the other performance measures significantly affected. There were no significant effects reported on performance during the pulse-modulated exposure condition (designed to represent a digital mobile phone-like signal).

Koivisto et al. (2000; 2000) reported 2 studies that examined cognitive performance during pulse modulated EMF exposure. There were 2 exposure conditions, sham exposure and active (a 902 MHz signal pulsed at 217 Hz) exposure, with a period of 24 hours between testing sessions in the first study (Koivisto et al., 2000), and participants tested twice within a single session in the second study (Koivisto et al., 2000). The first study aimed to examine the effects of mobile phone RF EMF on reaction times (Koivisto et al., 2000). The results showed a reduction in response times for simple reaction time and vigilance tasks, as well as a decrease in cognitive time spent in a mental arithmetic task, during exposure to the mobile phone RF

EMF. Accuracy in the vigilance task was also improved during the active exposure condition. The second study used the same exposure conditions to examine the effects of mobile phone RF EMF on working memory (Koivisto et al., 2000). The results showed a reduction in reaction times during RF EMF exposure, however, this effect was restricted to tasks with the heaviest memory load (three items), and was not present for the lower memory load (two items or less) conditions. There were no effects found between the active and sham exposure conditions for accuracy on the working memory tasks. However, the first study by this group (Koivisto et al., 2000) has been criticised for employing inappropriate statistical analyses on the data (IEGMP, 2000). That is, the effect of mobile phone exposure was assessed on the 14 measures of reaction time using separate pairwise statistical tests without first conducting a multivariate analysis to demonstrate if any general exposure effect existed. As type 1 error was not controlled for, the chance of finding a significant exposure effect was considerably higher than the significance level ($p < 0.05$) used to evaluate each test.

Following these two reports suggesting that mobile phone RF EMF emissions may have a facilitatory effect on cognitive function and performance, the same group of researchers attempted to replicate these studies using the same exposure conditions and parameters, as well as improving on the methodology by increasing the sample sizes and implementing a double blind study design. The previous effects on reaction time found by Koivisto et al (2000) were unable to be replicated when these stronger methodological controls were used (Haarala et al., 2003). This was also the case for the effects originally found on working memory (Koivisto et al., 2000), with the replication study finding no significant effects of mobile phone RF EMF on memory (Haarala et al., 2004). Given that the studies conducted by Haarala et al (2003; 2004) had a number of methodological improvements to the groups previous studies (Koivisto et al., 2000; Koivisto et al., 2000), including improvements in dosimetry, it has been suggested that the findings of the

original studies should be treated with some caution (Sienkiewicz et al., 2005).

In a different type of study, Lee et al (2001) examined the effects of mobile phone use on human attention by comparing regular mobile phone users (defined as GSM mobile phone users that had a reported phone use between 175 and 27,240 minutes) to a control group of non-mobile phone users matched for age and gender, using a number of different tests of attention. The results showed that the mobile phone user group performed significantly better on the Trail Making Test (a measure of cognitive ability specifically encompassing executive functioning and visuospatial abilities) than did the non-mobile phone users control group. There were no differences found between the groups on any of the other measures of attention performed. The same researchers followed this up with a human provocation study consisting of 2 experimental conditions – an active exposure condition consisting of a 1900 MHz GSM mobile phone signal, and a control/sham exposure condition (Lee et al., 2003). There were no effects found between groups for the Trail Making Test, however, similar to Koivisto et al. (2000) and Preece et al (1999), there was a significant decrease in reaction times on the Sustained Attention to Response Task (SART) in the RF EMF exposure condition compared to the sham condition.

Similar decreases in reaction times during cognitive tasks were also reported by Edelstyn and Oldershaw (2002) and Curcio et al (2004), however, in these two studies it was reported that reaction times were improved following RF EMF exposure, rather than during exposure, suggesting a delayed effect of mobile phone RF EMF on cognitive processing. However, in contrast to all of the previous studies on cognitive processes, the study conducted by Edelstyn and Oldershaw (2002) used a between-subjects experimental design, meaning that half of their participants received the active exposure, and the other half received the sham exposure. The limitation of using a between-subjects design is that the significant effects reported may in fact

have been due to individual differences in the participants rather than due to the mobile phone exposure, therefore making interpretations of this studies results difficult.

With the exception of one recent study, which found an increase in reaction times from participants' left hands during left hemisphere RF EMF exposure (Eliyahu et al., 2006), there has been a substantial number of studies that have recently reported no association between mobile phone type exposures and reaction times (Besset et al., 2005; Haarala et al., 2005; Preece et al., 2005; Hamblin et al., 2006; Regel et al., 2006; Russo et al., 2006), memory (Besset et al., 2005; Haarala et al., 2005; Preece et al., 2005; Papageorgiou et al., 2006; Regel et al., 2006), or vigilance (Besset et al., 2005; Haarala et al., 2005; Preece et al., 2005; Regel et al., 2006; Russo et al., 2006). Given that these recent studies have made a number of improvements to some of the methodologies used in previous studies, including more information regarding dosimetry and specific exposure parameters, in addition to the use of substantial sample sizes in some cases, this would suggest that the possibility of exposure to mobile phones influencing cognitive functioning is unlikely.

4.3.2 Mobile Phones and the EEG

The effects of mobile phone EMF on the brain have also been investigated using the EEG as a measure of bioeffects.

In order to examine the influence of mobile phone EMF on human brain activity, Reiser et al. (1995) exposed 36 participants for 15 minutes to an RF field originating from a digital mobile phone. The phone was positioned at a distance of 40cm from the participants head, with a peak output of 8 W and carrier frequency of 902 MHz (pulsed at a frequency of 217 Hz). The results suggested that mobile phone exposure causes an increase in EEG power in the Alpha-2 (9.75 - 12.5 Hz), Beta-1 (12.75 - 18.5 Hz), and Beta-2 (18.75 –

35 Hz) frequency ranges. This enhancement in EEG power was only found to be significant in the Beta-2 frequency range and was found to be most prominent in the occipital electrode measurements, which were closest to the site of exposure. However, the validity of these findings has been questioned, with suggestions that the findings may have been due to alterations in participant vigilance (Freude et al., 2000) rather than representing a delayed effect from the exposure as originally concluded by the authors (Reiser et al., 1995).

Roschke and Mann. (1997) also studied the influence of digital mobile phones on the awake EEG after an exploratory study revealed alterations in the quantitative sleep profile due to the effect of exposure to a GSM system (Mann and Roschke, 1996). Using a similar experimental design to Reiser et al. (1995), 34 male volunteers were exposed to a 900 MHz EMF emitted by the aerial of a digital mobile phone for three and a half minutes. The aerial was positioned at a distance of 40cm from the vertex of the subjects head and radiated at a peak power of 8 W. However, unlike Reiser et al. (1995) the authors reported no detectable alterations of the spontaneous awake EEG after digital mobile phone exposure.

Following this, Hietanen et al. (2000) performed a study to explore the possible influence of RF fields emitted by mobile phones on human brain activity. The study consisted of 19 participants, with five different sources of exposure being used (three analogue and one digital GSM mobile phone operating at 900 MHz, and one 1800 MHz digital personal communication network mobile phone), which were set to transmit at a maximum output power of 2 W. Each participant underwent 6 experimental sessions in which the EEG was recorded in an awake, closed-eye situation, with the mobile phone positioned at a distance of 1cm from the participants head in order to simulate normal use. The experimental sessions were conducted over a period of 6 days, one of which involved no field exposure, and the other 5 sessions consisting of 20 minutes of active exposure from the mobile phone

sources and 10 minutes of sham exposure. The authors reported that one of the analogue mobile phones caused a significant change in absolute power in the delta frequency band, however, there was no difference seen in the relative power of the same frequency band. No other effects were observed during exposure to the other phones tested, and given the large number of statistical tests conducted, the authors suggested that the effect seen in the delta frequency band was likely to be due to statistical chance.

Krause et al. (Krause et al., 2000), in a slightly different study, investigated the effects of mobile phone EMF exposure on the EEG while participants performed an auditory memory task. Using a similar design to Koivisto et al. (2000; 2000) – see section 4.3.1), 16 participants performed the memory task both with and without exposure to a digital 902 MHz mobile phone, which was mounted over the right posterior temporal region of the participants head for a duration of 30 minutes. The results showed that exposure to the EMF significantly increased EEG power in the 8 – 10 Hz frequency band, with no changes in EEG power seen for any of the other bands tested (4 – 6 Hz, 6 – 8 Hz, and 10 – 12 Hz). However, the presence of the EMF did alter event related desynchronisation (ERD) and synchronization (ERS) in the EEG as a function of both time and type of memory task performed, leading the authors to conclude that EMF exposure does not alter resting EEG, but modifies brain responses during memory tasks.

Following on from this study, Krause et al. (Krause et al., 2000) also investigated the effects of mobile phone EMF on the EEG during a visual working memory task. Using the same experimental design as their previous study (Krause et al., 2000), 24 participants performed a visual sequential letter task (n-back task) with three different working memory load conditions. In line with their previous findings, the results showed that mobile phone EMF exposure altered the ERD/ERS responses in the 6 – 8 Hz and 8 – 10 Hz frequency bands, but only as a function of memory load, and was also dependent on whether the presented stimulus was a target or not. Overall,

the authors concluded that mobile phone EMF affects specific EEG frequency bands in a task dependent manner, specifically around the 8 Hz region during cognitive processing.

Although both of these studies produced similar results, they also suffered from the limitation of using single-blind experimental designs, therefore, in a more recent study, the authors attempted to replicate the previous findings from their first study (Krause et al., 2000) using a more robust double-blind protocol (Krause et al., 2004). The only other change that was made from the previous study was that the phone was positioned over the left posterior temporal region, whereas previously it had been positioned to the right. However, the replication study failed to confirm the findings of Krause et al. (Krause et al., 2000) regarding the effects of mobile phone EMF on brain activity between 4 – 12 Hz during an auditory memory task. They also reported a significant increase in the number of incorrect answers during EMF exposure, which was not found in the earlier study. The only consistent finding between the two studies was that EMF exposure decreased the magnitude of the ERS responses in the 4 – 6 Hz frequency band (Krause et al., 2004). Given these inconsistencies in results across studies, the authors concluded that the effects of EMF on the EEG and performance during memory tasks may be variable, potentially due to individual differences in EEG, and therefore results are not easily able to be replicated.

In a study conducted by Huber et al. (2002), the effects of mobile phone EMF on the EEG were also assessed. In addition, this study also investigated the effects of RF EMF on regional cerebral blood flow (rCBF) and human sleep architecture (for discussion see sections 4.3.4 and 6.2, respectively). In a double-blind crossover design, 16 participants underwent three 30 minute exposure conditions (pulse modulated, continuous wave, and sham exposure), with each exposure condition separated by an interval of at least one week. The specific details of the EMF exposure used are discussed in 6.2. Spectral analysis of the EEG during waking revealed that following

pulse modulated exposure, EEG power in the alpha frequency range (8 – 13 Hz) was significantly increased compared to the sham exposure condition. This effect was not present following continuous wave exposure, leading the authors to conclude that pulse modulation of the EMF signal is a critical component for EMF-induced enhancements of EEG spectral power.

At a similar time, Croft et al. (2002) investigated the possible effects of mobile phone exposure on neural function in 24 participants. In a single-blind fully counterbalanced crossover design, participants underwent three consecutive 20 minute exposure conditions (active exposure, sham exposure, and a condition consisting of exposure to both the active signal and an EMF attenuator) in which the effects on resting EEG, and performance on an auditory discrimination task, were measured. The EMF exposure was applied using a standard Nokia 5110 mobile phone (900 MHz carrier signal, pulse modulated at 217 Hz, 0.577 µs pulse width), with an estimated average power of 3 – 4 mW and was positioned 5cm radial (midway between Oz and Pz electrode positions) to the participants scalp. The active mobile phone exposure was found to cause alterations in resting EEG, specifically decreasing delta activity (1 – 4 Hz) and increasing alpha activity (8 – 12 Hz) as a function of exposure duration. The authors concluded that mobile phone EMF exposure affects human neural function and does so as a function of exposure duration. However, this study was also limited by the single-blind experimental design and the lack of dosimetry regarding the EMF exposure applied, and therefore replication of this study is required in order to confirm the authors' conclusions.

Using a slightly different approach, Papageorgiou et al. (2004) investigated gender related differences in the EEG during mobile phone exposure. Nineteen participants (9 male; 10 female) were randomly exposed to both sham and active exposure conditions while performing a memory task. The exposure consisted of a 900 MHz signal emitted from the antenna of a mobile phone, with a mean power of 64 mW, positioned over the participants'

right hemisphere. The duration of exposure was approximately 45 minutes, with an interval of 2 weeks between exposure conditions. The results showed that EMF exposure caused a decrease in EEG spectral energy in the male participants, whereas in the female participants, a significant increase in energy was observed during exposure (specific frequency ranges where effects were found were not given). Regardless of these gender specific changes in EEG energy, there were no differences reported between males and females for performance on the memory task. The authors summarized their results by suggesting that mobile phones may affect brain activity, and that this effect appears to be gender related.

The most recent study to investigate the effects of mobile phone EMF on the EEG during resting wakefulness was reported by Curcio et al. (2005). The sample consisted of 20 participants who were randomly assigned to two groups, one which received exposure before the EEG recording, and the other receiving exposure during the EEG recording. Each participant underwent 3 exposure conditions (a baseline session, active exposure, and sham exposure), with at least 48 hours between each condition. Each exposure session lasted for 45 minutes, with group 1 receiving 45 minutes of exposure prior to the EEG recording, whereas the EEG recording for group 2 was performed during the last 7 minutes of the 45 minute EMF exposure. The mobile phone used for the exposure had a carrier frequency of 902.4 MHz (pulsed at 217 Hz) with a maximum power output of 2 W (average power 0.25 W). The phone was mounted on the left side of the participants' head using a helmet, and was positioned at a distance of 1.5cm from the participants' ear, which resulted in a maximum SAR of 0.5 W/Kg. The authors reported that exposure to the mobile phone EMF influenced a small range of frequencies in the alpha band, causing a significant increase in the 9 – 11 Hz frequency range. Furthermore, a temporal correspondence between the EMF exposure and the enhanced EEG power was also observed, with those participants exposed during the recording showing higher EEG power than those that were exposed prior to the recording. The authors concluded

that pulse modulated EMF influences brain activity and suggested that this influence was likely to be due to changes in cortical excitability. The main limitations of the study were in regards to sample size and effect size, which was also highlighted as a limitation by the authors, who suggested a note of caution should be taken when interpreting these results.

4.3.3 Mobile Phones and the EEG – Summary

A number of different methods have been used in order to investigate the possible effects of mobile phone EMF on the EEG and human neural function. The main measures reviewed that have been used as markers of possible RF bioeffects are resting EEG power, task-related EEG power, and event-related synchronisation (ERS) and desynchronisation (ERD). In addition to the number of different measures used, there has also been large variations in the exposures applied, particularly in regards to field intensity or power output, exposure duration, and type of exposure used (actual handset vs. antenna). All of the studies reviewed were limited by small sample sizes, with most studies using a sample of 24 participants or less (Hietanen et al., 2000; Krause et al., 2000; Krause et al., 2000; Croft et al., 2002; Huber et al., 2002; Papageorgiou et al., 2004; Curcio et al., 2005). Given that RF bioeffects are generally small, Cook et al. (2006) have suggested that non-significant results may be due to the lack of power to detect them, rather than the absence of an effect, and therefore researchers should take this statistical issue into account when designing future studies. Another consideration highlighted by Cook et al. (2006) is the laterality of EMF exposure applied, with different studies exposing different hemispheres (either right, left, or midline exposure), with no clear laterality effects between studies being shown to date. However, given that the exposure parameters differed vastly between the studies reviewed, research that applies more than one active exposure condition (e.g. left vs. right hemisphere exposure) may help to confirm whether the effects on the EEG are independent of the hemisphere exposed.

Regardless of the limitation and inconsistencies in the previous studies' methodologies, the majority of studies have still found a biological effect during and/or following mobile phone EMF exposure. Within these results, the most consistent effect has been the enhancement of EEG spectral power in the alpha frequency band due to mobile phone exposure, which has occurred both in the resting EEG scenarios as well as during cognitive task-oriented measurements. Although the particular alpha frequency at which these effects have occurred has varied, this could be due to a number of methodological factors, such as the differences in exposures. Another possibility for these variations is the individual differences in alpha activity among the participants (i.e. peak alpha frequencies vary across individuals; (Klimesch, 1997; Klimesch, 1999), as well as the possibility of individuals responding, or being affected differently by EMF exposure.

Based on the studies reviewed there is some evidence to suggest that mobile phone exposure could lead to alterations in brain activity, particularly in the alpha frequency band. However, further research that addresses the limitations of the previous studies needs to be conducted in order to confirm these effects on neural function and explore the mechanisms behind these effects.

4.3.4 Mobile Phones and Regional Cerebral Blood Flow

Following the increasing evidence that pulse modulated RF EMF leads to alterations in brain physiology, particularly during NREM sleep (see section 6.2) and also the EEG during waking, a number of recent studies have explored whether regional cerebral blood flow (rCBF) may also show alterations due to mobile phone EMF exposure.

Huber et al. (2002) conducted the first study investigating the effects of EMF on rCBF, in an experiment that also examined the effects on sleep (see

section 6.2) and the waking EEG (see section 4.3.2). The study consisted of 13 participants who underwent 2 exposure conditions (active pulse modulated EMF exposure and sham exposure), with the exposure directed to the left side of the head for a period of 30 minutes. Ten minutes after the end of the EMF exposure, positron emission tomography (PET) scans were taken in which participants were instructed to count slowly from 1 to 60 to ensure that cognitive activity was similar in both exposure conditions. Three PET scans were performed at intervals of 10 minutes, and in addition, a 10 minute transmission scan was performed at the end to correct for photon attenuation. Compared with the sham condition, it was found that pulse modulated EMF exposure increased relative rCBF in the dorsolateral prefrontal cortex ipsilateral to exposure. The authors suggested that the changes in rCBF following pulse modulated exposure could be due to alterations in cortical neuronal activity, which may in turn lead to modifications in cortico-thalamo-cortical loops involved in the generation of sleep spindles.

Haarala et al. (2003) claimed that the interpretation of the Huber et al. (2002) study was difficult due to the time between the EMF exposure and the PET measurements, and therefore conducted a study that aimed to investigate the effects on rCBF during mobile phone exposure. Fourteen participants were scanned using PET during 2 exposure conditions (sham and active exposure) in which they were required to perform a visual working memory task. The exposure was via a standard GSM digital mobile phone, which was mounted to the left side of the participants head, and emitted a 902 MHz signal (pulsed at 217 Hz, mean power 0.25 W) with a corresponding SAR measurement of 0.993 W/Kg (averaged over 10g). The results showed a bilateral decrease in rCBF in the auditory cortex, however, there were no changes in rCBF found in the area of maximum EMF exposure. Although the effect may have been caused by the EMF exposure, the authors suggested that, given the area that the effect was found in, it was more likely caused by

an auditory signal that was emitted by the mobile phone battery in the active exposure condition.

In order to further explore their original findings, Huber et al. (2005) attempted to replicate the effects that were previously found on rCBF and additionally investigate the comparison between handset-like and base-station-like exposure set-ups. Using the same study design as in the previous experiment, 16 participants were exposed for 30 minutes to the 3 exposure conditions (handset, base-station, and sham exposure), with an interval of at least 1 week between exposure sessions. Similar to the previous results, an increase in relative rCBF in the dorsolateral prefrontal cortex following the handset-like exposure was reported. The authors concluded that, due to the fact that the changes in rCBF were restricted to the handset exposure condition, the effect cannot be explained by a thermal action of the EMF, as the base station-like signal produced the same time-averaged energy as the handset signal. Therefore, the results provide further evidence that the pulse modulation of the RF EMF (present in mobile phone handsets but not base station signals) is crucial to induce changes in brain activity (Huber et al., 2005).

4.3.5 Mobile Phones and Regional Cerebral Blood Flow – Summary

Although only a small number of studies have been completed regarding the effects of RF EMF on rCBF, early indications suggest that EMF exposure can induce changes in rCBF. The differences in results observed between Huber et al. (2002; 2005) and Haarala et al. (2003) may reflect differences in the exposures used (antenna vs. handset exposure) as well as the differences in PET scan measurements (following exposure vs. during exposure). Particularly in regards to the timing of the PET scan, these initial results could indicate that the immediate effect of EMF on rCBF differs from the effects once exposure has ceased, and also suggests that EMF exposure may induce both immediate and delayed effects on rCBF. Additionally, although it

can sometimes be difficult to perform PET studies on large samples, replication of these studies with increased and more diverse samples would help to provide more definitive answers regarding the effects of EMF exposure on rCBF.

4.4 Summary

As the use of mobile phone technologies has increased, so too has the public concern regarding the possible health consequences related to mobile phone use. This concern has led to an increase in demand for scientific research on possible RF bioeffects induced by mobile phone use. Although arguably the largest concerns have been in regards to cancer, there has also been large concerns relating to effects on the brain due to the close proximity of the radiation emitted from the mobile phone handset when it is conventionally used next to the head.

In relation to cancer and brain tumours, there has been little evidence to date to support a causal relationship, however, the full analysis of the interphone study should provide more firm conclusions regarding possible cancer risk from mobile phone use.

Overall, there have been mixed reports regarding possible effects on cognitive functioning and brain activity. In regards to cognitive functioning, a number of early studies suggested that mobile phones may have induced small alterations in measures of cognitive performance such as reaction time, however, subsequent studies with improved methodologies have generally failed to find cognitive effects from mobile phone exposure. In contrast, the effects on the EEG have been slightly more consistent, with a number of studies observing effects in the alpha frequency range both during and following exposure. More powerful replication studies, with clearly defined dosimetry, may help to confirm the possibility of mobile phone induced

changes to the EEG, and combined with other measurement techniques (such as PET), the location and mechanisms behind these effects should also be investigated.

Chapter 5: Mobile Phones and Melatonin

The current chapter introduces previous research on the effects of mobile phone RF EMF on human melatonin production and secretion. A detailed review of the previous literature is provided, highlighting the study designs and reported results of the previous research, and concludes with a brief discussion regarding methodological considerations and the consistency of the reported mobile phone-induced effects on human melatonin.

5.1 Introduction

In addition to research regarding the effects of mobile phone RF EMF on tumours, cognition, the EEG, and rCBF, a number of recent studies have also investigated the possible effects of mobile phone RF EMF on the human neuroendocrine system. In particular, research has focussed on the pineal hormone melatonin, which has a fundamental role in the regulation of human biological rhythms, and has also recently been implicated as a powerful antioxidant. Melatonin production and secretion has also been widely used previously to study the biological effects of other types of EMF, such as static magnetic fields, pulsed magnetic fields, and alternating electromagnetic fields (Vollrath et al., 1997; Reiter, 1998).

5.2 Previous Investigations on Mobile Phone Emissions and Melatonin

The first investigation of RF bioeffects on human melatonin production was conducted by Mann et al. (Mann et al., 1998), who investigated the effects of pulsed high-frequency EMF on the neuroendocrine system. Using the same experimental exposure set-up as in a previous study on sleep (Mann and Roschke, 1996 - see chapter 6.2 for full details), nocturnal hormone profiles of growth hormone (GH), cortisol, luteineizing hormone (LH), and melatonin were determined at 20 minute (GH, LH, and cortisol) and 60 minute (melatonin) intervals throughout the night using a catheter to take blood samples during PSG recording. The results showed a transient elevation of cortisol serum levels during the active exposure condition, which was no longer present after one hour of exposure. No significant effects of exposure were found for the total production or secretion patterns of GH, LH, or melatonin. The authors concluded that high-frequency EMF has no effects on nocturnal hormone secretion, except for a slight elevation in cortisol production, which was a transient effect and suggests adaptation to the presence of EMF.

Using a different approach, De Seze et al. (1999) evaluated longer-term effects of mobile phone use on circadian patterns of melatonin secretion. The study sample consisted of 38 male volunteers (aged 20 – 32 years) who were exposed to a GSM mobile phone operating at 900 MHz (pulsed at 217 Hz) or a Digital Communication System (DCS) mobile phone that operated at 1800 MHz (pulsed at 217 Hz). Participants received exposure at maximum power, corresponding to a SAR of 0.3 W/kg, for 2 hours per day, 5 days a week, over a period of 4 weeks. Movies were projected during the 2-hour exposure period in order to sustain the participants' attention and prevent them from falling asleep. Blood samples were collected hourly during the night and at 3-hour intervals during the day on 4 separate occasions: before the beginning of the exposure period, at the middle and at the end of the

exposure period, and 15 days after the exposure period had ended in order to evaluate the possibility of delayed effects. The results showed that the circadian melatonin profile was not affected by mobile phone exposure, regardless of the type of phone used.

In order to help confirm the original results reported by Mann et al. (1998), Radon et al. (2001) investigated the possible effects of RF EMF on defined parameters of the human endocrine and immune systems. Eight healthy young male participants completed twenty 4-hour sessions (10 during the night, and 10 during the day) in a shielded experimental chamber. There was an interval of at least 2 days between day sessions and at least 3 days between night sessions. Saliva was collected every 30 minutes to determine levels of melatonin, cortisol, neopterin, and immunoglobulin A (sIgA) in each session. The active exposure was randomly applied in half of the experimental sessions (equally distributed among the day and night sessions) and consisted of a GSM 900 MHz carrier signal (pulsed at 217 Hz) that was applied via a circularly polarised antenna positioned at a distance of 10cm behind the participants' head. The power flux density was approximately 1 W/m^2 and the maximum local SAR in the head was measured to be 0.025 W/kg. The results showed that the salivary concentrations of melatonin, cortisol, neopterin, and sIgA did not differ significantly between the active and sham exposure conditions, which was consistent with previous observations of RF EMF effects on melatonin, but did not confirm the transient 1-hour increase in cortisol levels during the first hour of exposure reported by Mann et al. (1998).

Following these initial studies, Bortkiewicz et al. (2002) investigated possible effects of mobile phones on melatonin production by measuring the excretion of the melatonin metabolite 6-hydroxymelatonin sulfate (6-OHMS – also known as 6-sulphatoxymelatonin, aMT6s). Nine healthy young males underwent two 60-minute exposure sessions (sham and active) in the evening, with the active exposure consisting of a 900 MHz signal from a

mobile phone, pulsed at 217 Hz, with a SAR of 1.23 W/kg. Following exposure, participants listened to music for 4 hours until midnight, and then slept for a period of 7 hours until they were woken at 7 am. Participants were required to provide 3 urine samples, which were collected at 7 pm (prior to exposure), midnight (prior to sleep), and 7 am (following a 7-hour sleep episode). Mean 6-OHMS levels were not found to differ between exposure conditions for any of the urine collection time-points, and therefore the authors concluded that EMF emitted by mobile phones has no distinct influence on melatonin levels.

At a similar time, Burch et al. (2002) investigated the relationship between mobile phone use and the excretion of 6-OHMS in two populations of male electric utility workers. Participants were required to collect total overnight and post-work urine samples on 3 consecutive workdays. Mobile phone use for the 3-day study period was assessed by asking participants to record the amount of time spent using a mobile phone on each day of participation. Personal 60 Hz magnetic field and ambient light exposures were also characterised over the 3-day study period. No change in 6-OHMS excretion was observed in the first population of utility workers. However, utility workers in the second study population with daily mobile phone use greater than 25 minutes had lower creatinine-adjusted mean nocturnal 6-OHMS concentrations and decreased overnight 6-OHMS excretions compared with those who did not use a mobile phone during the study period. The authors also reported a linear trend of decreasing nocturnal 6-OHMS/creatinine concentrations and overnight 6-OHMS excretion as mobile phone use increased. From these results, the authors concluded that prolonged use of mobile phones may lead to reductions in melatonin production, however, the potential health consequences of a mobile phone-induced reduction in melatonin were unknown.

The most recent study was conducted by Jarupat et al. (2003), investigating the effects of 1900 MHz mobile phone EMF on nocturnal melatonin secretion.

The study consisted of 8 young female participants who underwent two exposure conditions (active and sham) on two separate days, in which they were exposed for 30 minutes continuously every hour between 19:00h and 01:00h. The active exposure was applied at a power density of 2.5 mW/cm^2, resulting in a whole-body average SAR between 0.453 – 0.680 W/kg. Melatonin production was assessed via salivary melatonin analysis, with samples of saliva collected at 19:00h and 02:00h. Similar to the results of Burch et al. (2002), the authors reported that average salivary melatonin was significantly lower in the active exposure condition compared with the sham exposure condition for the sample taken at 02:00h.

5.3 Methodological Limitations

There are some methodological issues and limitations in the previous studies on the effects of mobile phone EMF on melatonin production and secretion, making interpretations of the reported results somewhat difficult.

One methodological issue relates to the methods used to assess melatonin production or secretion, with measures of serum melatonin, salivary melatonin, and urinary melatonin metabolite used across the studies that have been reported to date. This makes comparison between studies somewhat difficult, and with the additional issue of large variations in time-points when the samples were taken, may help to account for some of the differences in results reported.

The other issue that may be responsible for the inconsistent results across studies relates to the exposure parameters used. There were large variations in the exposure signals applied, and also the duration and number of times that individuals were exposed (ranging from a single exposure of a few hours to exposures of several weeks).

The majority of studies were also limited statistically due to small sample sizes used, making it difficult to observe any small effects of mobile phone RF EMF on melatonin that may be present, and also leading to difficulties regarding conclusions and interpretations on reported effects.

5.4 Summary

Overall, there has been mixed reports regarding possible effects of mobile phone RF EMF on melatonin production and secretion (see Table 1 for summary), however, when effects have been observed they have shown reductions or suppressions in melatonin levels due to RF EMF exposure. Therefore, although previous research suggests that mobile phone exposure has a suppressive effect on melatonin secretion, a larger replication study that addresses the limitations of past studies (particularly in regards to clearly defined dosimetry and melatonin sampling time-points) is required to confirm these findings before any firm conclusions can be made regarding a mobile phone-induced suppression of melatonin or the possible consequences of this RF bioeffect.

Author	Group Size	Exposure details	Exposure duration	Number of repeats	Measure	Outcome
Laboratory studies						
Mann et al. 1998	24 M	Antenna 0.2 W/m^2 GSM-type	8 hr (23:00 – 07:00)	1 x Exposed; 1 x Sham	Serum melatonin, 60 min intervals	NS
de Seze et al. 1999	19 M	i) GSM and ii) 1.8 GHz DCS handset	2 hr/day (late afternoon)	Exposed 5 days/week for 4 weeks	Serum melatonin, 60 min intervals	NS
Radon et al. 2001	8 M	Antenna 1 W/m^2 (estimated SAR 25 mW/kg) GSM-type	4 hr/day (50% day, 50% night)	20 x Exposed; 5 x Sham	Salivary melatonin; 30 min intervals	NS
Bortkiewicz et al. 2002	9 M	900 MHz mobile phone handset (estimated SAR 1.23 W.kg)	1 hour (19:00 – 20:00)	1 x Exposed 1 x Sham	Urinary melatonin metabolite	NS
Jarupat et al. 2003	8 F	1.9 GHz mobile phone handset	6 x 30 min per hr (19:00 – 01:00)	1 x Exposed; 1 x Sham	Salivary melatonin, at 19:00 & 02:00	36% reduction for sample taken at 02:00
Population-based studies						
Burch et al. 2002 (Study 1)	149 M	Self-assessment of cell phone use	> 25 min/day compared to no use		Urinary melatonin metabolite	NS
Burch et al. 2002 (Study 2)	77 M	As above	As above		As above	34% reduction for overnight data

Table 1. *Comparison of human studies of mobile phone radiation and melatonin output. (NS = not significant).*

Chapter 6: Mobile Phones and Sleep

The current chapter introduces the importance of sleep research in answering bioelectromagnetics questions and highlights the advantages of using the sleep EEG as a measure of possible radiofrequency bioeffects. A detailed review of the previous literature on the effects of mobile phone and radiofrequency emissions on human sleep is then provided, highlighting the study designs and reported results of the previous research, and providing a discussion regarding methodological considerations and the consistency of the reported mobile phone-induced effects on human sleep.

6.1 Introduction

Research into the effects of mobile phone RF EMF on human sleep patterns and brain activity during sleep has been a more recent focus area of bioelectromagnetics research into the effects of mobile phones on human health and wellbeing. Several biological functions have been implicated that demonstrate the importance of human sleep, particularly in relation to energy conservation and restoration of depleted resources, but also in the consolidation of various cognitive abilities and memory function (see section 2.7). Therefore, any changes in sleep architecture, sleep quality, or the sleep EEG that may result from mobile phone use, could have important implications for human health and wellbeing.

Most studies investigating the effects of mobile phone RF EMF on human sleep have focussed on changes in sleep architecture, particularly changes in conventional sleep parameters such as sleep onset latency and the distribution of the different sleep stages, as well as alterations in the sleep EEG. The advantage of using the sleep EEG as a measure of biological

effects induced by RF fields emitted by mobile phones is that the EEG during sleep is well characterised and routinely used to identify the sleep stages and sleep cycle patterns that a typical healthy individual will move through during the night. This is in contrast to the EEG during wakefulness, where determining cortical events related to changes in EEG can sometimes be ambiguous, and therefore although alterations in the EEG may indicate a biological effect, interpretations of effects can often be uncertain (Hamblin and Wood, 2002). Conversely, there would be little uncertainty in the identification of a change from a normal, healthy pattern of sleep EEG to a pathological or abnormal sleep EEG pattern (for review, see Armitage, 2007), which further enhances the usefulness of sleep as an important tool for establishing possible RF bioeffects.

6.2 Previous Investigations on Mobile Phone Emissions and Human Sleep

In the first of a number of studies, Mann & Roschke (1996) investigated the effects of pulsed high-frequency EMF's on human sleep in 14 healthy male volunteers (two of which were excluded due to technical problems) aged between 21 and 34 years. Participants were exposed to a digital mobile phone that emitted a 900 MHz linear polarized electromagnetic field, pulsed at a frequency of 217 Hz. The phone was positioned at a distance of 40cm from the participants head and the radiated peak power of the aerial was 8W, resulting in an average power density of 0.5W/m^2 at the participants head. Each participant slept for 3 consecutive nights at the sleep laboratory, the first night being an adaptation night and the following 2 nights the participants received either active or sham exposure using a randomized EMF exposure schedule in a single-blind crossover design. The results showed that exposure to mobile phone RF EMF led to a decrease in sleep onset latency from 12.25 minutes to 9.5 minutes. In addition, when participants were under all-night exposure to the RF EMF there was a significant decrease in the

percentage of REM sleep, and an increase in EEG spectral power during REM sleep which was most pronounced in the alpha frequency range, compared to the sham exposure condition. No other significant effects were found for other conventional sleep parameters, however, a tendency for an increase in REM sleep latency was also reported. The authors concluded from these results that exposure to RF EMF may lead to alterations in sleep architecture and sleep regulation due to the hypnotic effect on sleep latency and the suppression of REM sleep that were observed. However, they also stated that the mechanisms of these effects on sleep regulation were unknown (Mann and Roschke, 1996).

Following these results the same research group attempted to replicate the findings by investigating human sleep under the influence of pulsed RF EMF in 24 healthy male participants (Wagner et al., 1998). In a similar experiment to Mann & Roschke (1996), all night polysomnographies were recorded both with and without all-night exposure to a digital mobile phone. The mobile phone used emitted a 900 MHz field (pulsed at a frequency of 217 Hz) from a circular polarized antenna, positioned 40cm below the pillow of the bed. This resulted in an average power density of 0.2W/m² at the participants' head, compared with 0.5W/m² used in the groups previous study. SAR values were also calculated, with 0.3W/kg measured at the vertex and a maximum SAR of 0.6W/kg measured at the back of the neck. Statistical analysis failed to reveal any significant changes in conventional sleep parameters under RF EMF exposure, although a tendency for a reduction in sleep onset latency (from 15.92 minutes to 15.32 minutes) and a trend level suppression of REM sleep (a reduction in the average amount of REM sleep and an increase in REM sleep latency) were reported. Results concerning spectral power of the EEG during sleep also failed to show any significant differences between the presence and absence of the RF EMF exposure. This discrepancy in results between the two studies was accounted for by the authors as being due to differences in the physical qualities of the EMF applied, particularly in regards

to the type of antenna and average power flux density used (Wagner et al., 1998).

These results prompted the same investigators to repeat the experiment (Wagner et al., 2000) with the assumption that the effects of the RF EMF may be dose-dependent, which would provide a possible explanation of why only trend level effects were found by Wagner et al. (1998) who had used a lower power density than in the original study that showed a significant reduction in sleep onset latency and REM sleep suppression (Mann and Roschke, 1996). In a somewhat different protocol, 20 healthy male participants spent two phases in the sleep laboratory, with each phase consisting of either two consecutive active exposure nights or two consecutive sham exposure nights. Each phase was preceded by an adaptation night and there was an interval of at least 7 days between each exposure phase. The exposure consisted of a circular polarized EMF generated by a horn antenna which was connected to a digital mobile phone. The antenna emitted a 900 MHz field (pulsed at 217 Hz) and was once again positioned 40cm below the pillow of the bed. The average power density at the participants head was 50W/m², a significantly higher power density than had been used in the groups previous two studies. However, the results showed no significant effects of the RF EMF exposure on conventional sleep parameters or on the sleep EEG spectral power, despite the increased power flux density applied. The authors discussed these findings and suggested that the differences in results across the three studies may be due to a non-linear or window effect, where sleep is only affected by RF EMF exposure in a particular range of power flux densities (Wagner et al., 2000). The authors also highlighted the possibility of individual differences in response and sensitivity to RF EMF exposures, as well as the differences in the physical qualities of the EMF applied across the three experiments, as being possible factors for the inconsistent results.

In order to help clarify the inconsistent results of previous investigations, Borbely et al. (1999) conducted a study looking at the effects of pulsed high-frequency EMF on human sleep and the sleep EEG. The participants were 24 healthy young male volunteers and they were exposed during an entire night-time sleep episode to an intermittent radiation schedule of alternating 15 minutes on/15 minutes off intervals. The exposure consisted of a simulated pulse-modulated GSM signal at 900 MHz using a linear polarized antenna positioned at a distance of 30cm from the participants' head. The signal was modulated with frequencies used by mobile phone handsets and base stations (2, 8, 217, 1736 Hz) and had a base station like duty cycle of 87.5%, as compared with a 12.5% duty cycle normally employed by mobile phone handsets. The maximum SAR during exposure was set not to exceed 1W/kg. Each participant attended a screening night followed by two experimental nights. There was an interval of one week between the experimental nights, and both experimental nights were preceded by an adaptation night. The adaptation nights were recorded in a different room to the experimental nights. The EMF exposure schedule used on the experimental nights consisted of a randomly assigned, double-blind crossover design. The results indicated that exposure to the pulse modulated EMF reduced the duration of waking after sleep onset (WASO), which was significant for the entire sleep episode. A reduction in WASO would suggest a sleep promoting effect of the EMF exposure. Furthermore, EEG spectral power was significantly enhanced in the 7.25 -14.25 Hz frequency range during the first NREM sleep episode. Further analysis revealed that EEG power in the 11.5 – 12.25 Hz and 13.5 – 14 Hz frequency ranges was increased during the first 30 minutes after lights out, meaning that the EEG had been affected at these frequencies after only 15 minutes of EMF exposure (Huber et al., 2003). Power in these frequency ranges correspond to alpha activity and to frequencies associated with slow and fast sleep spindle activity. Unlike the earlier work of Mann and Roschke (1996), there were no differences found between the exposure conditions on the EEG during REM sleep (Borbely et al., 1999). The authors concluded that

only a short exposure of 15 – 30 minutes was necessary to exert changes in the sleep EEG, and the fact that significant changes were restricted to the initial part of the sleep episode would suggest the presence of an adaptation mechanism to the EMF exposure.

These results led the same group of researchers to investigate the effect of exposure to pulsed high-frequency EMF during waking on a subsequent sleep episode (Huber et al., 2000). The participants consisted of 16 healthy, young, right-handed males who underwent exposure to a 900 MHz carrier signal that used the same frequency modulations and duty cycle as the groups first experiment (Borbely et al., 1999). Exposure was applied unilaterally from an antenna positioned at a distance of 11cm from the participants' head, with an input power of 2.2 W, which resulted in a spatial peak SAR value of 1 W/kg. The experiment consisted of three exposure conditions (right hemisphere, left hemisphere, and sham exposure) using a randomized, sham-exposure controlled double-blind crossover design, and there was an interval of one week between each exposure condition. The participants were exposed to the EMF for a period of 30 minutes prior to a 3 hour daytime sleep episode, and they were also moderately sleep deprived due to their sleep in the preceding night being restricted to 4 hours. In contrast to the groups first study (Borbely et al., 1999), the results showed no significant effects of EMF exposure on WASO, or any other conventional sleep parameters (Huber et al., 2000). However, consistent with the previous findings, spectral analysis of the EEG during sleep revealed a significant enhancement of EEG spectral power following EMF exposure in the 9.75 – 11.25 Hz and 12.25 -13.25 Hz frequency ranges. This effect was only observed in the first 30 minutes of NREM sleep and was no longer present at the end of the 3 hour sleep episode. In addition, the unilateral exposure conditions demonstrated similar effects in both left and right hemispheres, and therefore no lateralisation of the effect was observed. The authors concluded that exposure to EMF during waking affects the EEG during subsequent sleep, but that this effect is transitory and restricted to the initial

part of sleep. The enhancement of EEG spectral power was found in similar frequency ranges to those reported in the first study (Borbely et al., 1999), corresponding to alpha and sleep spindle activity, and therefore the authors concluded that spindle generating mechanisms may be particularly susceptible to EMF exposure associated with digital mobile phones (Huber et al., 2000).

At a similar time, another group of researchers were also investigating the effects of mobile phone EMF exposure on human sleep (Lebedeva et al., 2001). Twenty male volunteers underwent 2 nights at a sleep laboratory, where they were exposed during an 8 hour sleep episode to the EMF of a standard GSM mobile phone on one night, and a simulated/sham signal on the other night. Although in a previous study investigating awake EEG (Lebedeva et al., 2000) participants were exposed for 15 minutes to an EMF at a frequency of 902.4 MHz, with an intensity of 0.06 mW/m^2, information regarding specific exposure parameters in the present sleep study was not provided. The researchers reported that exposure to EMF caused a significant increase in EEG spectral power in the alpha frequency range, with a similar tendency found in the theta and delta ranges. A significant decrease in the two-channel correlation dimension D2, which is a measure of the nonlinear dynamics of the EEG, was also found under EMF exposure. In addition, exposure to EMF was reported to lead to a tendency for slow wave sleep to decrease compared to sham exposure. From these results the authors concluded that the EMF from a mobile phone affects sleep structure and results in a reduction of slow wave sleep and REM sleep percentage. The authors also concluded that these changes were able to decrease a person's adaptive reactions, and as a result, lead to impairments in human health.

In a third experiment, Huber et al. (2002) once again investigated the effects of mobile phone EMF on the EEG during both sleep and wakefulness, as well as effects on regional cerebral blood flow (see section 4.3.4). Sixteen

healthy, young male right-handed participants were exposed, using a double-blind crossover design, for 30 minutes to either a pulse modulated, continuous wave (non-modulated), or sham exposure at the left hemisphere prior to an 8 hour sleep episode. Each participant underwent all 3 exposure conditions and each exposure night was preceded by an adaptation night. The EMF exposure consisted of a 900 MHz carrier frequency and the pulse modulated signal used the same modulation components as their previous 2 studies (2, 8, 217, 1736 Hz and the corresponding harmonics), however, the previously used duty cycle of 87.5 % was replaced with a 12.5 % duty cycle in order to more accurately simulate a mobile phone handset signal. The results revealed that conventional sleep parameters were not significantly affected by EMF exposure. Analysis of the EEG prior to sleep onset revealed an increase in spectral power in the alpha frequency range. This effect was only present in the pulse modulated exposure condition and was not found after the continuous wave or sham exposure conditions. The sleep EEG also showed alterations following pulse modulated EMF exposure, with an increase of spectral power in the 12.25 – 13.5 Hz frequency range in stage 2 NREM sleep. The enhancement of power in this frequency range, which is typically associated with the presence of sleep spindles, followed the general increasing trend of normal spindle frequency activity, and therefore was found to be largest in the 4th and 5th NREM sleep episodes. This is contrast to the researchers' previous studies (Borbely et al., 1999; Huber et al., 2000) in which EMF exposure did not have a long-lasting effect. The authors concluded that pulse modulation of the EMF signal was critical in order to induce enhancements in EEG spectral power during sleep and wakefulness. They also emphasized that the observed changes in the EEG were subtle, and despite these subtle changes, sleep stage distribution and other conventional sleep parameters, such as sleep onset latency, were not affected by exposure to EMF and therefore it would be premature to draw any conclusions regarding health consequences.

The most recent laboratory study to be reported investigated human sleep under the influence of a GSM 1800 MHz signal in the far field (Hinrichs et al., 2005). In a double-blind crossover design, 14 volunteers (predominantly female) spent five consecutive nights in a sleep laboratory, the first of which was an adaptation night, and the following four nights were randomly assigned exposure nights consisting of two nights with active exposure and two nights with sham exposure. The EMF exposure was applied continuously throughout the night and approximated a base station-like signal using a signal generator and flat panel antenna, providing a vertically polarized GSM signal at 1800 MHz (pulse frequency of 1736 Hz) with a field strength of 30 V/m and power flux density of 2.3 W/m^2. The antenna was positioned at a distance of 1.5m from the participants' head, with the maximum SAR estimated to be 0.072 W/kg (averaged over 10g). There were no significant differences found between the exposure conditions for any of the conventional sleep parameters measured. Furthermore, spectral analysis of the EEG during sleep failed to show any differences between the EMF exposure and sham exposure conditions. From these results the authors concluded that there was no evidence to support a causal relationship between GSM 1800 MHz base station emissions and sleep disturbances.

6.3 Methodological Limitations

There are many methodological issues and limitations in the previous studies on the effects of mobile phone EMF on human sleep that make interpretations of the research studies somewhat difficult.

The carrier frequencies used to simulate digital GSM mobile phone signals were all 900 MHz (with the exception of 1800 MHz base station carrier frequency used by Hinrichs et al., 2005) and were modulated at 217Hz with a pulse width of either 577 or 580µs. This is consistent with the signals

typically used in GSM mobile phones and the use of these frequencies and modulations was maintained throughout all of the studies. Not only does this allow for comparisons between the studies in relation to carrier frequencies, but is also relevant in regards to the generalizability of the results, as the same signals are employed in the GSM phones used by the general population.

Some of the earlier studies (Mann and Roschke, 1996; Wagner et al., 1998; Wagner et al., 2000) studies were conducted single-blind with only the participant being unaware of the presence or absence of the electromagnetic field. This does not control for any experimenter effects or bias resulting from the investigator knowing which treatment the participant was receiving, and therefore results from these studies must be interpreted with caution.

However, the most important methodological issues for research into the effects of mobile phone emissions on sleep are to keep exposures and experimental designs consistent and realistic to actual mobile phone use and sleep-wake cycles, which did not occur in the majority of the previous research studies. The use of more realistic exposure conditions would help to clarify whether the effects that have been reported are likely to occur during or following normal mobile phone use, or whether they appear to result from the high powers or exposure durations predominantly used in previous studies.

Although most of the studies were intended to investigate the effects of mobile phone exposure on human sleep and the sleep EEG, many variations in exposure parameters existed. Some studies employed the use of base station-like emissions, with duty cycles much larger than those of mobile phone handsets. Substantial differences in power output, exposure periods, and distances from the source of exposure were also prominent. These inconsistencies in exposure may partly explain the diversities in outcomes observed.

Many of the studies used power outputs much larger than those emitted from a typical mobile phone handset, which in some cases was to help compensate for the distance between the participant and the source of exposure. The peak power emitted by a digital GSM 900 MHz mobile phone is 2W, with the average power output never more than 0.25W (IEGMP, 2000). Continuous power outputs much larger than this at 8W were used in the studies of Mann & Roschke (1996) and Wagner et al. (1998; 2000), with all of the other studies using lower values that were still much larger than that of a mobile phone handset. Furthermore, a number of studies did not report sufficient information regarding the SAR of the exposure administered, which not only makes interpretations and comparison of results difficult, but also does not allow for replication as the SAR is an important dosimetric parameter for evaluating both the power of the signal applied and also to verify that the exposure complies with exposure limits (Kuster et al., 2004).

The distances between the participants' head and exposure source also varied from 11cm to 40cm (and up to 1.5m in the study investigating far field exposures), which was directly related to the differences in power output. Although this design set-up was presumably aimed to maintain normal and relatively comfortable sleeping conditions, the unrealistic nature of this exposure poses problems for interpretation, particularly as it does not resemble normal mobile phone use or the specific localized exposure that a user would typically receive, but rather produces an overly homogonous field approaching a more far field-type exposure that is quite different from the exposure gradients that typically occur in the near field.

Another source of variability was the duration of exposure that the participants' received. In many of the studies, the participants were exposed to a continuous signal of 8W for the whole 8-hour sleep episode. This duration of exposure does not attempt to simulate normal mobile phone use, and the practical application of such an exposure is somewhat questionable

as use or exposure does not normally occur during sleep. Similarly questionable is the application of a 15 minutes on – 15 minutes off intermittent signal used by Borbely et al. (1999), which also does not represent conventional mobile phone use. Exceptions to this were the studies of Huber et al. (2000; 2002) who applied exposure for 30 minutes prior to sleep, which aimed to more accurately simulate typical mobile phone use.

None of the studies used the phone in a position directly next to the head to resemble the position that mobile phones would normally be used in, and differences in the signals used, either real or simulated, was also a source of variance. A real phone positioned at the head would seem desirable to make the results more accurately representive of typical mobile phone use, however, there are both advantages and disadvantages in using actual and modified mobile phones, compared with exposures from antennas placed at a distance. One advantage of using a real or modified mobile phone over an antenna for exposure in human laboratory studies is that the exposure is comparable to real-life use. For example, SAR distributions resulting from real mobile phone handsets are substantially different to those resulting from antennas designed to simulate mobile phone signals (Boutry et al., 2007). In relation to this, some studies have actually indicated that their studies may not apply to typical mobile phone use. In particular, Wagner et al. (1998) attempted to replicate their previous experiment (Mann and Roschke, 1996) but used a different antenna and power flux density to that previously used. Not only did the authors attempt to justify the discrepancy in results by referring to the different exposure parameters used, but also reported that the results could not be generalized to mobile phone technologies anyway, as the type of antenna used was different to those used in mobile phones.
However, one disadvantage of using an actual phone lies in the differences in energy absorption patterns that occur with different mobile phone models, which is the advantage of using an antenna that is able to deliver exposure to the entire area of the head that might receive energy from a mobile phone

during normal use, regardless of the model (Kuster et al., 2004). Due to both the use of an actual handset and an antenna having drawbacks, it would seem desirable, if possible, to conduct studies using both types of exposure systems in order to compare whether the highly localized exposure from the handset elicits the same or similar responses to the less localized exposure gained from an antenna.

Most studies attempted to account for disturbances in sleep that may have occurred due to the experimental conditions by including an adaptation night in the experimental design. However, the study conducted by Huber et al. (2000) used sleep deprived participants and measured the effects of EMF exposure during short daytime sleep episodes, which does not resemble normal sleeping patterns and therefore makes interpretations and comparisons with other studies difficult.

One considerable problem in the interpretation of experimental studies is that many of them give insufficient details regarding the exposure conditions and parameters used. This was particularly the case in the study by Lebedeva et al. (2001), which provided little or no information concerning carrier signals and frequency modulations used, power outputs, and durations, distances, and set-up of the exposure applied. They also did not provide statistical significance levels for some of the findings reported. Furthermore, the authors' interpretations of their results, stating that mobile phones affect sleep structure, possibly leading to health impairments are completely unfounded, as there is currently no evidence to suggest that the low level effects of RF EMF that have been observed on human sleep lead to health consequences and there were no measures of health or wellbeing reported by the authors to support this conclusion. In light of these insufficient experimental design details and questionable conclusions, interpretation of this study is extremely difficult.

The main statistical limitation in the majority of studies reviewed was the small sample sizes used. Studies with a reasonably adequate sample size of 24 participants were Wagner et al. (1998; 2000), and Borbely et al. (1999). All of the other studies reviewed were conducted with 20 participants or less, decreasing the statistical power to detect small effects, which would seem particularly problematic in this area of research where the effects are likely to be small or subtle. The sample types used were, however, similar in nature, with most studies applying EMF exposure to healthy young male participants. Although this makes results between studies more comparable, it also produces limitations in generalizing the results to the much wider population of mobile phone users.

6.4 Summary

Taken together, the findings from the previous studies investigating the effects of EMF on human sleep would suggest that exposure to GSM mobile phone emissions influence brain activity during sleep (see Table 2 for summary of results), however, as mentioned previously (see section 6.3), direct comparisons between the studies is difficult due to the large variations in exposure parameters and methodologies used.

Some studies have shown that exposure to EMF, both during sleep and prior to sleep onset, result in enhancement of EEG spectral power. However, this enhancement of EEG spectral power has been observed during both REM sleep (Mann and Roschke, 1996), and more commonly, during NREM (Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003) sleep stages. The frequencies at which these EMF induced changes have been found has also varied, with both the alpha and spindle frequency ranges being affected. Furthermore, although the changes in EEG have been reported more consistently during NREM sleep, some studies have found the increases in EEG spectral power to be greatest during the first

NREM sleep episode (Borbely et al., 1999; Huber et al., 2000), while one study found that the enhancements in EEG spectral power increased over the course of the night with each subsequent NREM period (Huber et al., 2002).

In addition, other conventional sleep parameters that have been reported to exhibit effects due to EMF exposure include sleep onset latency, the duration of waking after sleep onset (WASO), and the percentage and latency of REM sleep. These findings have been inconsistent and unable to be replicated, particularly when improved methodologies have been used.

Overall, the effects of mobile phone EMF on human sleep have been largely inconsistent, as there has been no clear effects found on conventional sleep parameters, and the enhancement of EEG spectral power, which has been found somewhat more consistently, has varied in frequency range, the sleep stage effected (REM or NREM), and the time-course of the effect. These inconsistencies may be due to a number of limitations in the studies reviewed. In particular, the use of single-blind techniques in some of the studies, the small sample sizes used, and perhaps most importantly, the large variations, and in some cases inadequate or non-relevant dosimetry and exposure parameters used.

In regards to sample size and sample characteristics, nearly all of the previous studies had less than 20 participants, and the participants predominantly used were young, healthy males. The use of larger samples would increase the statistical power of future studies, and investigations using more diverse samples, such as the inclusion of both males and females and wider age ranges, would also be beneficial in making the results more generalisable, and would also allow for the possibility of investigations to address whether there are differences between the effects of EMF on different demographics, such as age and gender. Additionally, the growing popularity of mobile phones among adolescents should also prompt research

into possible influences on younger people's sleep processes and development, as to date, no studies have investigated the effect of mobile phone use on adolescents sleep.

In relation to dosimetry and the exposure parameters used, there has been little consistency in the previous studies, with large variations in exposure durations, distances from the source of the exposure, power outputs, SAR values, exposure type and modulations (base-station and handset-like signals), and antennas used, which has been the biggest limitation in the previous research and may help account for the variations in EEG frequency range enhancements that have been found, suggesting that the particular frequency subcomponent may be sensitive to differences in methodology. Future research should aim to address these limitations, and in particular, not only should the duration of exposure be kept within realistic parameters, but exposure designs and dosimetry should also be clearly defined when reporting results. Where possible, research that attempts to use experimental designs that replicate the actual or worst-case exposure conditions typically received by the use of mobile phone technologies, would lead to more meaningful and interpretable results, which would in turn help to address public concerns surrounding mobile phone use.

In relation to reported effects of mobile phone EMF on the sleep EEG, the choice of exposure time and duration (prior to sleep vs. during sleep) should be carefully selected and justified according to the purpose of the study. For example, if the aim of the study is to investigate effects on sleep of typical mobile phone use, then a short exposure prior to sleep would seem appropriate, whereas if the aim is to investigate the worst case scenario or effects of maximum possible exposures, then an extended exposure duration prior to sleep or exposure throughout the night would be a more appropriate choice. Another consideration is the attachment of electrodes, and if electrodes are attached during exposure (which occurred in all of the reviewed studies), the effect of this should also be addressed as it has

previously been shown that the presence and placement of electrodes during exposure leads to changes in the spatial peak SAR values measured (Huber et al., 2003). Furthermore, the use of normal sleeping hours and routines would be beneficial as it would help to eliminate the confound of effects being influenced by changes in sleep patterns, and may also help to clarify the inconsistent results regarding the enhancement of EEG spectral power.

Although the most consistent part of the literature suggests that mobile phone EMF influences brain activity during sleep, few have attempted to address the biological or clinical significance of such an effect and its relevance to the safety of mobile phone communications. Wagner et al., (1998) suggested that the alterations they observed in REM sleep may lead to disturbances in learning functions due to the important role that REM sleep is believed to play in information processing, and Huber et al., (2000) also postulated from their results that the thalamus, which is involved in the generation of sleep spindles, may be particularly sensitive to EMF, therefore explaining why enhancements in EEG have occurred somewhat consistently in the spindle frequency range. However, most of the studies have regarded their own findings, and those of others, as being insufficient to draw any conclusions regarding health consequences or effects on human wellbeing. This was also emphasized in a recent review (Danker-Hopfe and Dorn, 2005), claiming that the effects observed to date, particularly those relating to quantitative sleep EEG analysis, did not necessarily indicate an impairment of health.

The previous studies also do not allow for speculations on any long-term effects on sleep that may occur from mobile phone exposure and use over an extended period of time. However, the findings regarding changes in the EEG from acute or short-term exposures have mostly been transitory, which may suggest an adaptation mechanism to the EMF exposure, and therefore the possibility of long-term effects related to the changes in EEG would seem unlikely. Nevertheless, given the current uncertainty regarding bioeffects

from mobile phone exposure, particularly in relation to the results concerning sleep which have varied across studies, both short-term and long-term exposures should be addressed in future studies in order to confirm not only the presence of an effect on sleep or the sleep EEG, but also to determine the mechanisms and consequences of these effects from mobile phone exposure.

Overall, previous research on the effects of mobile phones on human sleep has suffered from a number of methodological limitations, making interpretations of the results somewhat difficult. However, regardless of these limitations, studies have shown a somewhat consistent effect on the sleep EEG from mobile phone-like EMF exposures, and therefore, replication of these studies, using improved methodologies, is warranted to clarify the effects of mobile phones on sleep, and also to help address the growing public concerns regarding mobile phone use.

Study	Exposure Parameters	Results
Mann & Roschke, 1996	• GSM phone (900 MHz) • 40cm from head • 8 W peak power; 0.5 W/m² average power density • 8 hours continuous exposure	• ↓ sleep latency • ↓ REM sleep % • ↑ REM sleep EEG power (7.5-12.5 Hz) • ↑ REM sleep EEG power (12.5-15 Hz)
Wagner et al., 1998	• Circular polarised flat antenna (900 MHz) • 40cm from head • 0.2 W/m² average power density • SAR = 0.3 W/Kg at vertex; SAR = 0.6 W/Kg at back of neck • 8 hours continuous exposure	• No significant changes in sleep parameters • No significant alteration of EEG during sleep
Wagner et al., 2000	• Circular polarised horn antenna (900 MHz) • 40cm from head • 50 W/m² average power density • 8 hours continuous exposure	• No significant changes in sleep parameters • No significant alteration of EEG during sleep
Borbely et al., 1999	• Linear polarised antenna (900 MHz); 87.5 % duty cycle • 30cm from head • SAR = 1 W/Kg • Intermittent exposure (15 mins on/15 mins off) for 8 hours	• ↓ WASO • ↑ NREM sleep EEG power (7.25-14.25 Hz) • ↑ NREM sleep EEG power (11.5-12.25 Hz and 13.5-14Hz) in first 30 minutes of sleep
Huber et al., 2000	• Planar, rectangular patch antennas (900 MHz); 87.5 % duty cycle • 11cm from head • SAR = 1 W/Kg • 30 mins exposure prior to a 3-hour daytime sleep episode	• No significant changes in sleep parameters • ↑ NREM sleep EEG power (9.75-11.25 Hz) • ↑ NREM sleep EEG power (12.25-13.25 Hz)
Lebedeva et al., 2001	• Mobile phone – specific exposure parameters not provided	• No significant changes in sleep parameters • ↑ EEG power (alpha) • ↓ Correlation dimension D2
Huber et al., 2002	• Planar antennas (900 MHz); 12.5% duty cycle • 11cm from head • SAR = 1W/Kg • 30 mins exposure prior to full night-time sleep episode	• No significant changes in sleep parameters • ↑ NREM sleep EEG power (12.25-13.5 Hz)
Hinrichs et al., 2005	• Flat panel antenna (1800 MHz) • 1.5m from head • 30V/m field strength; 2.3 W/m² average power density • SAR = 0.072 W/Kg • 8 hours continuous exposure	• No significant changes in sleep parameters • No significant alteration of EEG during sleep

Table 2. *Summary of previous results on the effects of mobile phone RF EMF on human sleep.*

Chapter 7: The Experiment - The Effects of Electromagnetic Fields Emitted by Mobile Phones on Human Sleep and Melatonin Production

7.1 Introduction and Overall Purpose

As described in the previous chapters, the use of mobile phones has continued to increase over the past few years, and due to this increase in use there has also been an increase in research into the possibility of effects arising from exposure to the RF EMF emitted by mobile phone handsets. Of particular interest are the effects digital mobile phone emissions may have on conventional sleep parameters and the sleep electroencephalogram (EEG), as well as the secretion of the pineal hormone melatonin. A number of studies have reported an increase in EEG spectral power within the 8–14 Hz frequency range, in both awake (Reiser et al., 1995; Croft et al., 2002; Cook et al., 2004) and sleep states following radiofrequency EMF exposure (Mann and Roschke, 1996; Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003). Enhancements reported during sleep, however, have not been entirely consistent, with some earlier studies failing to find an effect (Mann et al., 1998; Wagner et al., 1998; Wagner et al., 2000), and others finding that the effects differ in terms of particular frequency band (Mann and Roschke, 1996; Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003). These reported inconsistencies following mobile phone exposures are likely to be due to a number of methodological issues (see section 6.3 for review), such as small sample sizes, variations in power output, different exposure durations, and distances from the source of exposure. Differences in duration of sleep episodes measured may also contribute, with substantial variation in these ranging from short daytime sleep episodes with sleep-deprived volunteers, to full overnight sleep

episodes. It is thus not surprising that there are differences in study outcomes, and it is noteworthy that there have been several reports of enhanced sleep spectral power in the 8–15 Hz frequency range following radiofrequency EMF exposure (Mann and Roschke, 1996; Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003).

Thus, although there are complexities in the literature, there is support for an enhancement in EEG spectral power during non-REM sleep, with the variability in the frequency ranges suggesting that the particular frequency subcomponent may be sensitive to differences in methodology. In addition to changes in spectral power, other conventional sleep parameters, such as sleep latency, rapid eye movement (REM) sleep, and waking after sleep onset, have also been reported to be affected by radiofrequency EMF exposure (Mann and Roschke, 1996; Wagner et al., 1998; Borbely et al., 1999). Unlike spectral power changes, however, there is no consistency in the conventional sleep parameter findings. Further, that the original positive findings (Mann and Roschke, 1996; Borbely et al., 1999) have been tested with stronger methodological control (including dosimetry) and resulted in negative outcomes, this suggests that there are no effects of radiofrequency EMF on conventional sleep parameters (Mann et al., 1998; Wagner et al., 1998; Huber et al., 2000; Wagner et al., 2000; Huber et al., 2002). Previous results regarding the effects of mobile phone RF EMF on melatonin production have also been somewhat inconsistent, with no clear indication of melatonin being affected by mobile phone emissions, with some studies showing no effect (Mann et al., 1998; de Seze et al., 1999; Radon et al., 2001) and others reporting significant reductions in melatonin secretion (Burch et al., 2002; Jarupat et al., 2003). However, as with the studies investigating sleep architecture and the sleep EEG, the studies on melatonin have also had a number of methodological inconsistencies, particularly in relation to exposure parameters used and the methods used to assess melatonin output.

Due to the substantial worldwide use of mobile phones and to date, the lack of consistent findings regarding the effects of RF EMF on human sleep and melatonin production, the current study was designed to improve on previous methodological limitations in order to help clarify the current state of knowledge regarding RF bioeffects on sleep and melatonin from mobile phone emissions.

7.2 Aims

The aims of the current study were thus to test for the immediate effects of mobile phone radiofrequency EMF on human sleep patterns and the secretion of the pineal hormone, melatonin. In order to improve on previous research limitations and simulate real-life exposure conditions and sleep habits, the present study exposed participants to pulsed high frequency EMF emitted by an actual mobile phone handset, with continuous transmission and constant power output, for a period of 30 minutes prior to a full night-time sleep episode. Also in addressing previous exposure limitations, the current study aimed to provide detailed information regarding the dosimetry of the exposure set-up used (see section 9.4), and in addition, all electrodes and monitoring equipment was not placed on the participants until after the exposure had finished in order to avoid any alterations or interference with the EMF signal emitted from the mobile phone. The current study also aimed to address statistical issues related to multiple comparisons in the EEG spectral power analyses of previous studies, and therefore only performed hypothesis driven statistical analyses on three pre-defined frequency ranges, with all other frequencies treated as purely exploratory, and adjustments for multiple comparisons made where appropriate. Furthermore, the previous limitations regarding sample sizes and single-blind protocols have also been addressed, with the current study being conducted double-blind with a randomised exposure schedule, and also employing a significant increase in

the sample size making it the largest study to date to investigate the effects of mobile phone emissions on human sleep.

7.3 Hypotheses

The current study attempted to replicate the more consistent work of Huber et al., (Huber et al., 2002; Huber et al., 2003) and test the hypotheses that EEG spectral power in the 11.5–12.25, 12.25–13.5, and 13.5–14Hz frequency bands would be enhanced following radiofrequency EMF exposure during the first NREM sleep period. In regards to subsequent NREM sleep periods, it was hypothesised that there would be no significant changes in EEG spectral power following mobile phone exposure. Additionally, it was hypothesised that radiofrequency EMF exposure would not influence conventional sleep parameters. In regards to melatonin secretion, it was hypothesised that exposure to mobile phone RF EMF prior to sleep would cause a reduction in overnight melatonin secretion, as measured by the melatonin metabolite 6-sulphatoxy melatonin. Each of these parameters, being hypothesis driven, were analysed and considered significant at $p < 0.05$ (see Tabachnick and Fidell, 1989).

7.4 Exploratory Analyses

In addition to the analyses on the three pre-defined frequency bands in both the first NREM period and across NREM periods throughout the night, a number of exploratory analyses were also performed to investigate whether there were any effects at other frequencies, and also whether the EEG during REM sleep was altered due to mobile phone EMF exposure. Each 0.25 Hz frequency bin between 0 and 25 Hz was analysed for each NREM and REM period separately, as conducting a 2 x 4 repeated measures ANOVA would have excluded too many participants due to only a small number of

participants having a fourth NREM or fourth REM period in both exposure conditions. Furthermore, as the analysis of every 0.25 Hz frequency bin resulted in 800 comparisons, a simple Bonferroni correction was deemed to be inappropriate as this procedure is known to be too conservative when there are a number of endpoints to be analysed, and when the endpoints are highly correlated. Therefore, the Dubey / Armitage & Parmar correction method was used in order to maintain an overall alpha level of 0.05 for the exploratory analyses (Sankoh et al., 1997). This method is similar to the Bonferroni correction, however, it also takes into account the mean correlation between all of the dependent variables and therefore reduces the possibility of increases in Type II error. This procedure has also been used previously for analysis of the EEG in bioelectromagnetics research (Curcio et al., 2004). Therefore, following this adjustment for multiple comparisons, all exploratory analyses were considered significant at $p < 0.001$.

Chapter 8: Materials and Methods – Study Design

8.1 Participants

8.1.1 Recruitment and Selection Criteria

Participants were recruited by notices placed in local newspapers, the sleep laboratory, and around the university campus, and also through interviews with the investigators on national radio and television programs. The selection criteria stipulated that participants were to be between the ages of 18 and 70 years, and were not to be currently suffering from, or have suffered previously from, any sleep disorders, epilepsy, or other serious medical illnesses or mental health problems. There were no requirements regarding previous or current mobile phone use.

8.1.2 Sample Characteristics

Fifty-five healthy volunteers[2] (30 male and 25 female), aged between 18 and 60 years (mean = 30.6 years, SD = 13.4 years), were recruited to participate in the study. Of these participants, 5 were found to be suffering from respiratory-related sleep disorders and were therefore removed from all EEG and sleep architecture analyses. This reduced the sample to 50 participants (27 male and 23 female) aged between 18 and 60 (mean = 27.9 years, SD = 10.9 years). Participants were provided with a detailed copy of the study information and protocols prior to participation (appendix A), and if they understood and agreed with the study procedures, they were required to sign a consent form. All participants were informed that they were free to withdraw from participation at any stage throughout the study. The project

[2] Pilot data used in honours thesis to test the validity of the study design.

was carried out according to the National Statement on Ethical Conduct in Research Involving Humans (June 1999) produced by the National Health and Medical Research Council of Australia (NHMRC) and the study was approved by the Human Research Ethics Committee of Swinburne University and the Ethics Committee at the Alfred Hospital, Melbourne, Australia. Participants received financial reimbursement for their time and travel costs.

8.1.3 General Laboratory Details

All recordings were conducted at the Eastern Sleep Disorders Service (ESDS), Mitcham Private Hospital, Victoria, Australia. This purpose-built sleep laboratory consists of 3 individual bedrooms with video monitoring, a central control room, one bathroom, and a joint lounge and kitchen area. The building was centrally heated with a constant room temperature of 20°C (± 1°C).

8.2 Experimental Design

8.2.1 General Experimental Design

Participants slept a total of four nights (22:30 – 06:00 hrs) in the sleep laboratory, attending two experimental sessions 1 week apart. Each of the two experimental nights was preceded by an adaptation night to help participants acclimatize to the laboratory conditions and also to rule out the presence of any sleep disorders. The experimental nights consisted of a randomized EMF exposure schedule using a double-blind crossover design. Participants were randomly exposed to either 'active' or 'sham' (see section 7.2.4) exposure condition for 30 minutes prior to a full night-time sleep episode, receiving the opposite condition on their second experimental night. Immediately after the 30 min of active/sham phone exposure, and upon waking in the morning, participants were required to perform a urine

collection. Participants were also required to abstain from caffeine and alcohol once they had arrived at the laboratory and were restricted from using mobile phones or communication devices on all of the adaptation and experimental nights.

8.2.2 Sleep-Wake History

Participants were required to maintain a regular sleep-wake schedule for the week prior to each experimental night. Participants were also required to fill out a sleep diary (appendix B) detailing their sleep patterns over the 2 weeks of participation, including the 4 nights spent at the laboratory. This diary was used to confirm that participants had kept a regular sleep-wake schedule, and also to look at subjective perceptions of participants' sleep on the experimental nights spent at the laboratory.

8.2.3 Polysomnographic Recordings

Participants sleep was assessed using polysomnographic recordings on all of the adaptation and experimental nights. This consisted of 2 EEG channels (C3-A2 and C4-A1), EOG (LOC and ROC), submental electromyogram (EMG), a 2-lead ECG, SaO2 pulse oximetry, nasal airflow (thermistor), thoracic and abdominal respiration, body position, and leg movements (Figure 12 and Figure 13), using the Compumedics S-Series polysomnography system (Compumedics Ltd, Abbotsford, Victoria, Australia). Respiratory measures and leg signals were used as exclusion measures only and were not included in any analyses. Sleep signals were sampled at 125 Hz or 250 Hz depending on specific equipment used. EEG signals were high-pass filtered at 0.3 Hz and low-pass filtered at 30 Hz. All EEG impedances were below 5 kΩ at the start of each recording. In order to minimise the possibility of interference with the EMF signal from the mobile phone, all electrodes and sensors were attached following exposure, leaving approximately 20 minutes between the end of exposure and lights off.

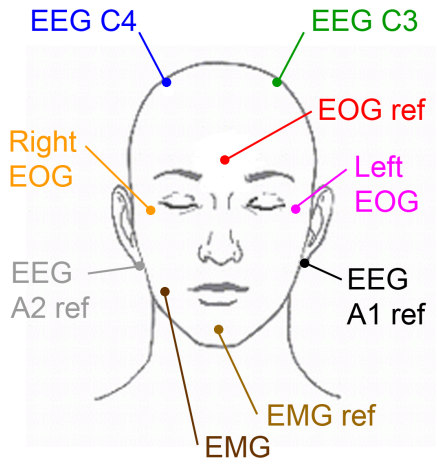

Figure 12. *EEG, EOG, and EMG electrode placement.*

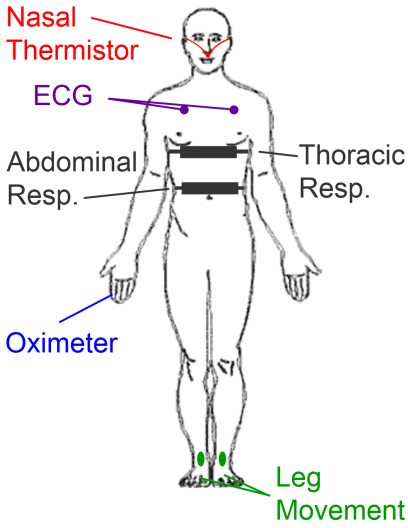

Figure 13. *ECG, Respiratory band, Thermistor, leg movement, and oximeter placement.*

8.2.4 Electromagnetic Field Exposure

On both experimental nights participants sat comfortably in a chair with a mobile phone head cradle placed on the head. A standard GSM digital mobile phone was mounted on the right side of the head cradle and positioned so that the speaker was located over the auditory canal and the antenna situated over the right temporal region, with the microphone aligned towards the corner of the mouth in order to simulate normal use (Figure 14). The cradle could be adjusted for different head sizes which ensured that the mobile phone did not move during exposure and also allowed for greater participant comfort.

Figure 14. *Head cradle and positioning of GSM mobile phone.*

The GSM digital mobile phone used in all experimental sessions was a modified Nokia 6110 (Nokia Group, Helsinki, Finland). For the purposes of exposure hazard evaluation, it was assumed that the radiated power would be the maximum permissible, although it is unlikely for this to occur in real life situations because of the use of adaptive power control (see section 3.4). Therefore, for the active condition, a data cable connected to a laptop computer and software provided by the manufacturer was used to set the phone to continuously transmit at a peak power of 2 W, with a mean power output of 0.25 W. In the sham condition the phone was turned off. Phone outputs were checked by an independent laboratory (the Australian Radiation Protection and Nuclear Safety Agency) three times during the course of the project. The signal emitted by the antenna was an 894.6 MHz radiofrequency field pulsed with a frequency of 217 Hz and a duty cycle of 12.5%, resulting in a pulse width of 576 µs. The 26th frame was not idle, and

therefore there was no 8 Hz component in the exposure signal[3]. The audio circuits of the phone were disconnected and foam padding was placed between the handset and its cover to ensure that both the researcher and the participants were not given acoustic cues revealing the operational status of the phone. The padding also served to eliminate or reduce any heat being felt by the participant that may have been generated from extended battery operation, further ensuring that the status of the phone was unable to be identified. The measurements of the thickness of the foam padding and mobile phone cover are shown in Table 3.

Measurement Area	**Thickness**
Front of cover (top – including foam padding)	5.5 mm
Front of cover (middle)	1.2 mm
Front of cover (bottom)	1.2 mm
Right side of cover	1.4 mm
Left side of cover	1.5 mm

Table 3. *Measurements of the thickness (± 0.1 mm) of the leather mobile phone cover and foam padding which were designed to attach the phone to the head cradle and eliminate any acoustic or temperature cues of the phones' operational status.*

Additionally, a white noise generator was used in the background in order to mask any residual sound from the handset's operation. Participants were asked at the conclusion of the experiment whether they had been able to detect when the phone was transmitting (see section 10.1).

[3] Measurements conducted by Nicholas Perentos in collaboration with Ray McKenzie and the Telstra Research Laboratories.

8.2.5 Urine Collection

Participants were instructed not to pass urine after 20:00 h on both of the experimental nights. Following 30 minutes of either active or sham exposure, participants were required to collect a urine sample which involved measuring and recording the total amount of urine voided, taking a 10ml sample which was later frozen, and discarding the remainder. This exact process of urine collection was also completed in the morning immediately after the participant had been woken at 06:00 h and electrodes had been removed.

8.2.6 Questionnaires

All participants completed the NEO PI-R personality inventory (appendix C) on the first adaptation night, and the Profile of Mood States (POMS – appendix D) on each experimental night prior to exposure. The NEO PI-R measures interpersonal, motivational, emotional, and attitudinal styles of adults, while the POMS assesses mood states, with both of these measures being used to assess if any important differences were present between individuals, and also to assess any differences within individuals in regards to mood on the experimental nights.

An electric and magnetic fields (EMF) exposure questionnaire (appendix E) was given to assess possible electromagnetic hypersensitivity as well as to determine each participants average use of a mobile phone handset and other appliances that emit RF fields.

On each experimental night, participants were also required to fill out a demographics questionnaire (appendix F), giving details such as age, gender, menstrual cycle phase (female participants), health and medical history, and consumption and use of substances such as caffeine, alcohol, and illicit drugs.

8.2.7 Data Analysis – Sleep Architecture

Sleep stages were visually scored by an experienced sleep technician for each 30 second epoch according to the standard criteria of Rechtschaffen and Kales (1968). The sleep technician was unaware of the experimental conditions. Sleep onset was defined as the first occurrence of stage 2 sleep (Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003). The staging and scoring of the polysomnographic recordings resulted in 10 conventional sleep parameters (Table 4) that were analysed for the active and sham exposure conditions. As the analysis in regards to conventional sleep parameters was treated as exploratory, a repeated measures analysis of variance (ANOVA) was performed on each of the 10 sleep parameters and no Bonferroni correction was applied.

Sleep Parameter	Definition
Total sleep time	*The total amount of time that the participant was asleep.*
Sleep onset latency	*The interval between lights out/start of recording and the first occurrence of stage 2 sleep.*
REM latency	*The interval between sleep onset and the onset of the first REM sleep period.*
Arousal index	*The number of wakings or arousals per hour after sleep onset.*
Sleep efficiency	*The total sleep time expressed as a percentage of total time spent in bed.*
Stage 1 sleep	*The total amount of time spent in stage 1 sleep.*
Stage 2 sleep	*The total amount of time spent in stage 2 sleep*
Slow-wave sleep (SWS)	*The total amount of time spent in slow-wave sleep (stages 3 – 4).*
NREM sleep	*The total amount of time spent in NREM sleep (stages 1 – 4).*
REM sleep	*The total amount of time spent in REM sleep.*

Table 4. *The ten conventional sleep parameters that were identified for analysis and their corresponding definitions.*

The polysomnographic recordings were then converted to European Data Format (EDF) for further analysis. Using Matlab software (Natick, Massachusetts, USA), the first six channels of each recording (C3, C4, L-EOG, R-EOG, EMG, ECG) were extracted and recombined in a format compatible with Neuroscan Edit software (Compumedics Ltd), which was

used for all subsequent analyses. Artefact removal was performed by visual inspection and only artefact-free epochs were used for further analysis. C3 and C4 data were averaged together and power spectral density estimates were calculated (Fast Fourier transform routine, Hanning window, averages over 4-second epochs) for each consecutive epoch of data in each REM sleep period and for the first 30 minutes of each NREM sleep period. All statistical analyses were performed using SPSS statistical package version 11.5 (SPSS Inc., Chicago, Illinois, USA).

8.2.8 Data Analysis – Melatonin Concentrations

The concentration of the melatonin metabolite, 6-sulphatoxymelatonin (aMT6s, also known as 6-OHMS), was estimated in duplicate via 125I radio-immunoassay on the urine samples provided by the participants on the experimental nights and mornings. The radio-immunoassay was performed in collaboration with the ProSearch International laboratory (Malvern, Victoria, Australia) using an assay kit supplied by Stockgrand Ltd (Guildford, UK). Additionally, determination of urine creatinine (Cr) was performed by ARL Pathology (Melbourne, Australia) in order to provide a standardized measure of aMT6s. All statistical analyses were performed using Excel.

Chapter 9: Materials and Methods – Dosimetric Evaluation[4]

9.1 Introduction

Previous studies investigating the effects of mobile phone RF EMF on human sleep and the brain have varied widely in regards to the exposure source used, ranging from using an actual or modified mobile phone handset (for example, Mann and Roschke, 1996), to using different antennas that have been specifically designed for health risk assessment (for example, Huber et al., 2003). Although the use of vastly different exposure systems can lead to difficulties in the comparison of results, perhaps the most important issue that has existed in the majority of previous studies is the poorly defined exposure parameters and the lack of detailed dosimetric data, which can lead to uncertainties in interpretation as well as making the replication of studies difficult. Most previous studies have only provided limited dosimetric information, if any has been provided at all, which has largely focussed on reporting the peak spatial SAR as determined by the procedures used for compliance testing in relation to safety guidelines. However, it has been suggested that the peak spatial SAR as developed for compliance testing can be a very poor and misleading metric to describe exposure, as it correlates poorly to the exposed brain regions and does not provide any information about the location of maximum absorption (Kuster et al., 2004; Boutry et al., 2007). Therefore, given the importance of having sufficiently detailed dosimetric information for both interpretation and replication of study results, a detailed dosimetric evaluation was carried out post-experiment for

[4] The dosimetric evaluation was performed in collaboration with Prof. Niels Kuster at the IT'IS Foundation, Zurich, Switzerland.

the Nokia 6110 exposure set-up used in the current study in collaboration with Professor Niels Kuster and the IT'IS Foundation.

9.2 Comparison of Exposure Systems

As discussed in previous chapters, past research has used a number of different exposure methods to investigate the effects of mobile phone RF EMF on the brain, cognition, and human sleep. The majority of previous studies have, however, used one of either two set-ups: an antenna configuration (such as the planar patch antenna's used by Huber et al., 2003) or a modified mobile phone handset (such as the Nokia 6110 used in the current study and by Haarala et al., 2004). Although neither exposure system is *a priori* better than the other, there are distinct advantages and disadvantages associated with both systems which should be addressed by researchers prior to designing a study, as the patterns and levels of exposure differ significantly between the two set-ups (Boutry et al., 2007).

In regards to the planar antenna set-ups that have been used in a number of the previous studies on sleep (for example, Huber et al., 2000; 2002; 2003), there are a number of benefits as they are well characterised, reproducible, and easy to implement. They also provide a very uniform exposure of one side of the entire cortex, which is very useful for investigating RF bioeffects (anywhere in the head rather than just at the surface) at SAR levels approaching the exposure limits, regardless of whether these levels of exposure would be expected to occur in every day phone use. This is an important function of the planar antenna exposure systems and studies using this set-up are essential to ensure that the current exposure standards and guidelines are adequately set in order to protect human health and well-being. However, one disadvantage of using an antenna system such as those used by Huber et al. (2003), is that the exposures are not representative of a 'typical' mobile phone exposure and have been shown to

result in a SAR in particular areas of the brain up to 100 times that of what would occur from using a real mobile phone handset as the exposure system at the maximum allowable level (Boutry et al., 2007). Therefore, studies using such antenna configurations with emissions approaching the limits set in the exposure standards should not be used to evaluate the direct effects of mobile phones, as the degree and pattern of exposure is not representative of a 'typical' mobile phone exposure.

The other type of exposure set-ups used in studies investigating RF bioeffects are modified mobile phone handsets. The benefits of using an actual mobile phone are that they are generally cost-efficient and provide an exposure that is characteristic of what would occur in every day life exposure, thereby providing a direct assessment of effects that may be induced by exposure to the RF EMF emitted by an mobile phone. However, one limitation of using an actual mobile phone handset is that each mobile phone model has a unique footprint of exposure that differs from phone to phone (Boutry et al., 2007). Additionally, the exposure pattern can change as a function of the position of the mobile phone with respect to the head, and therefore studies using this type of exposure set-up should ensure that a system is implemented to eliminate or minimise variations in phone position during the experimental testing.

Overall, it is clear that the exposures produced by antenna configurations and mobile phone-type set-ups are significantly different, with the planar antenna system more suited for assessing exposure limits or worst-case scenario exposures, whereas modified mobile phone handsets are better suited to test for effects more directly related to normal mobile phone use and exposures. Given this, researchers should endeavour to select a particular exposure system that is based on the specific purposes of the study.

9.3 Experimental and Numerical Methods

The detailed dosimetric analysis of the Nokia 6110 used in the current study was conducted inside a SAM phantom which was filled with tissue-simulating liquid that was specifically designed to meet the requirements of the dielectric tissue parameters at frequencies around 900 MHz (see Table 5 for dielectric parameters of the specific tissue types).

Tissue Type	**ε_r**	**σ[S/m]**
Bone (cancellous)	20.8	0.34
Brain (grey matter)	52.7	0.94
Brain (white matter)	38.9	0.59
Cerebellum	49.4	1.26
Cerebro-spinal fluid	68.6	2.41
Cornea	55.2	1.39
Ear (avg. skin and cartilage)	42.0	0.82
Fat	5.5	0.05
Lens	41.2	0.64
Lower jaw	20.8	0.34
Mastoid bone	20.8	0.34
Midbrain	52.7	0.94
Muscle	55.0	0.94
Nasal cavity	1.0	0.00
Pterygiod muscle	55.0	0.94
Skin	41.4	0.87
Skull	16.6	0.24
Spinal cord	52.7	0.94
Spine	20.8	0.34
Thalamus	52.7	0.94
Tongue	55.3	0.94
Upper jaw	20.8	0.34
Lateral ventricles	68.6	2.41
Vitreous humor	68.9	1.64

Table 5. *Dielectric parameters of the specific tissue types discriminated in the human head model (relative permittivity ε_r and conductivity σ at 900 MHz) (Gabriel, 1996).*

The measurements were conducted using the precision RF near-field Dosimetric Assessment System (DASY4)(Figure 15a), which is based on a high precision 6-axis robot that positions the SAR measurement probes with a positional repeatability of better than ± 0.02mm. The actual Nokia 6110 used in the current study was mounted on the SAM phantom (Figure 15b) and flat phantom (Figure 15c) for dosimetric evaluation, and the antenna input power was derived from the measurements with the SAM phantom (Figure 15d) for different phone positions using a least square fit (Boutry et al., 2007).

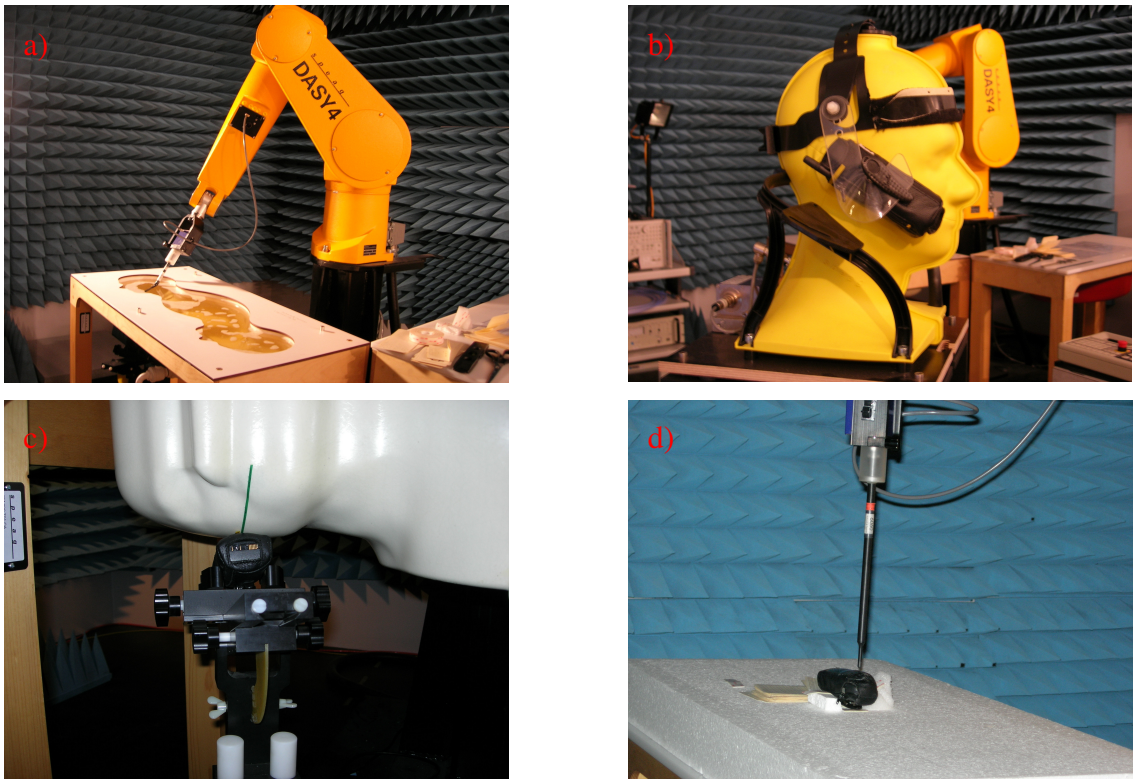

Figure 15. *a) DASY4 performing SAR measurements inside the flat phantom filled with tissue-simulating liquid; b) The Nokia 6110 mounted on the SAM phantom; c) The Nokia 6110 mounted on the flat phantom; d) Measurement of antenna input power.*

9.4 Dosimetric and SAR Results

The dosimetric analysis provided detailed information regarding the SAR distributions, uncertainties, and variations (including different postures and phone positions, and different head sizes). The tissue model and SAR distribution for the Nokia 6110 are shown in Figure 16. The peak spatial SAR averaged over 1g of the cortex was 0.19 W/kg. The 1g averaged peak spatial SAR values and the averaged SAR values for the different tissues are shown in Table 6.

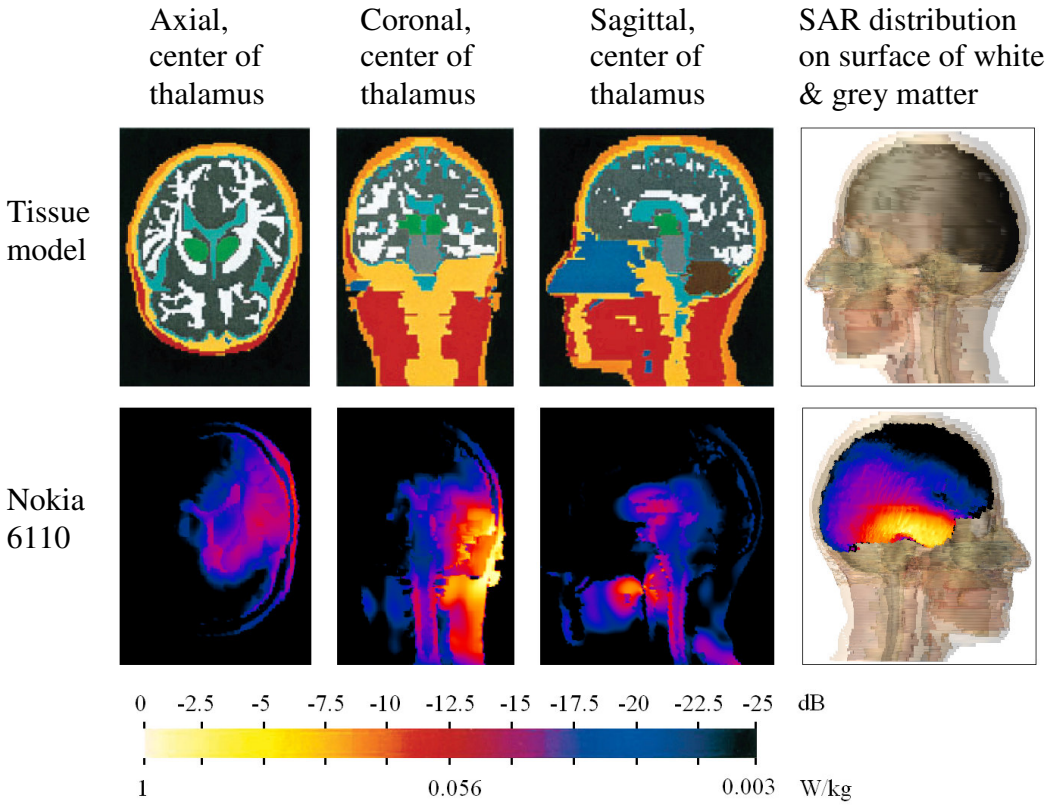

Figure 16. *Computed distribution of the specific absorption rate (SAR) for the tissue model and the SAR distribution for the Nokia 6110 (adapted from, Boutry et al., 2007). The Nokia 6110 exposure resulted in a very localised exposure of the upper cheek and inner ear regions, and concentrated on a limited area of the middle temporal gyrus just above the ear.*

	Right Hemisphere				Left Hemisphere			
	1 g[a] mW/kg	avg.[b] mW/kg	SD[c] mW/kg	Loss.[d] mW	1 g[a] mW/kg	avg.[b] mW/kg	SD[c] mW/kg	Loss.[d] mW
Brain grey matter	187	13.2	24.8	5.96	6.91	0.91	1.01	0.39
Brain white matter	125	13.3	23.3	2.21	3.35	0.50	0.47	0.10
Grey & white matter	172	13.2	24.4	8.18	6.89	0.78	0.89	0.49
Thalamus	10.8	8.32	2.31	0.05	6.30	3.84	1.67	0.023
Brain avg. without v. 1.[e]	247	15.3	32.8	12.5	29.0	1.30	2.57	1.09
Brain avg.	247	15.3	32.8	12.5	29.0	1.30	2.57	1.10
Total head	901	37.7	95.7	88.3	81.6	1.79	4.56	4.10

Table 6. *Specific absorption rate (SAR) of the different head tissues (including brain grey matter, brain white matter, cerebellum, midbrain, thalamus, cerebro-spinal fluid, and ventricular lateralis) for the right and left hemispheres during right hemisphere exposure (adapted from, Boutry et al., 2007).*

[a] peak spatial SAR averaged over a cube of 1g tissue

[b] tissue averaged SAR

[c] standard deviation of the averaged SAR

[d] total power losses

[e] brain average without ventriculus lateralis

	Both Hemispheres				Variation[f]		Uncertainty[f]	
	1 g[a]	avg.[b]	SD[c]	Loss.[d]	1 g	avg.[b]	1 g	avg.[b]
	mW/kg	mW/kg	mW/kg	mW	%	%	%	%
Brain grey matter	187	7.09	18.5	6.27	20	33	23	23
Brain white matter	125	6.18	16.6	2.28	20	31	23	23
Grey & white matter	172	6.82	18.0	8.55	20	32	23	23
Thalamus	10.8	5.93	2.94	0.071	46	55	30	31
Brain avg. without v. 1.[e]	247	8.06	23.7	13.4	20	34	23	23
Brain avg.	247	8.08	23.7	13.4	20	34	23	23
Total head	901	19.7	69.7	91.2	18	26	23	22

Table 6 (continued). Specific absorption rate (SAR) of the different head tissues (including brain grey matter, brain white matter, cerebellum, midbrain, thalamus, cerebro-spinal fluid, and ventricular lateralis) for both hemispheres combined during right hemisphere exposure, with variations and uncertainties (adapted from, Boutry et al., 2007).

[a] peak spatial SAR averaged over a cube of 1g tissue

[b] tissue averaged SAR

[c] standard deviation of the averaged SAR

[d] total power losses

[e] brain average without ventriculus lateralis

[f] variation and uncertainty for k = 1 or coverage factor of 66%

Analysis also revealed a higher combined uncertainty for the thalamus compared to the other tissues evaluated (see Table 6), which was explained by the thalamus' higher dependence on the dielectric parameters (Boutry et al., 2007). Additionally, it was observed that variation in head anatomy and head size were the main contributors to the total variability in SAR distribution. The local and peak spatial SAR was also more sensitive to head size, which led to more variation in SAR than when the head-phone position was varied.

9.5 Summary

The dosimetric evaluation provides a clear and detailed dosimetry for the Nokia 6110 mobile phone exposure set-up used in the current study, following the guidelines of Kuster et al. (2004). The SAR evaluations showed that the exposure set-up results in a very localised exposure of the upper cheek and inner ear regions, which was concentrated in the area of the middle temporal gyrus just above the ear (Boutry et al., 2007). Variability analysis also confirmed that the procedure used for mounting the mobile phone to the participants head was adequate, as factors other than phone position, such as head size, were found to contribute more to the overall variability in SAR. The peak spatial SAR in brain tissue of 0.19 W/kg and the pattern of SAR distribution was also deemed to be representative of an exposure pattern that would be expected from a mobile phone handset, and therefore it was concluded that any results from the current study would be generalisable to normal, short-term, mobile phone use.

Chapter 10: Results

10.1 Preliminary Analyses

Results from the EMF exposure questionnaire revealed that the participants' median values for reported mobile phone daily use and years of mobile phone use were 8 min per day for average daily use and 4 years for average time period since first mobile phone use (see appendix E for more details on the use of hands-free devices and reports of subjective symptoms). The means, medians, and standard deviations for the participants' average phone use per day in the last week and last year, as well as total years of phone use are shown in Table 7.

	Mean	Median	SD
Phone use per day in last week (minutes)	15.56	8.0	30.01
Phone use per day in last year (minutes)	15.97	10.0	30.85
Years of phone use	4.73	4.0	2.81

Table 7. *Frequency of mobile phone use (n=49)*

As condition order was not perfectly balanced due to 5 participants being excluded who were found to be suffering from respiratory related sleep disorders (24 had sham followed by exposure, 26 had exposure followed by

sham), this factor was included in all of the analyses and was not found to significantly relate to the experimental manipulation. Additionally, participants were asked at the conclusion of the experiment if they had been able to detect when the phone was transmitting. Only 27 out of 50 participants correctly classified the status of the phone. This number was not greater than chance (Binomial distribution, p=0.672), and this number was still not significant when those that were unsure (and had been forced to make a choice as to whether the phone was transmitting or not) were removed from the analysis (27 out of 44 correct responses, p=0.174).

10.2 EMF and Conventional Sleep Parameters[5]

A repeated-measures analysis of variance revealed a decrease in REM sleep latency following pulse-modulated EMF exposure ($F(1,48) = 5.797$, $p = 0.02$). The REM latency for the active condition was 90.17 minutes, showing a reduction of approximately 17 minutes from the REM latency in the sham condition, which was 107.77 minutes (Table 8). There was no significant difference found in total sleep time, sleep onset latency, arousal index, sleep efficiency, or the percentage of stage 1 sleep, stage 2 sleep, slow-wave sleep, NREM sleep, and REM sleep between the sham and active exposure conditions (Table 8).

[5] The analysis of conventional sleep parameters has been published by Loughran et al. (2005) in Neuroreport (see appendix G).

	Sham	Active	*p* values
Total sleep time (min)	323.1 (46.86)	324.4 (44.42)	0.844
Sleep onset latency (min)	37.37 (39.42)	36.97 (32.5)	0.956
REM latency (min)	107.77 (56.43)	90.17 (42.57)	**0.020**
Arousal index (per hour)	9.76 (4.16)	10.41 (3.2)	0.162
Sleep efficiency (%)	88.18 (7.85)	88.56 (8.65)	0.739
Stage 1 (min)	10.75 (5.79)	11.65 (5.16)	0.195
Stage 2 (min)	150.82 (41.37)	148.17 (41.56)	0.613
Slow-wave sleep	101.86 (29.4)	102.31 (28.36)	0.895
NREM sleep (%)	81.74 (6.23)	81.74 (5.87)	0.988
REM Sleep (min)	59.63 (21.5)	59.79 (21.39)	0.949

Table 8. *Effects of EMF exposure on visually scored sleep variables (Loughran et al., 2005). All night mean values (standard deviation in parentheses for n = 50). Sleep variables based on visual scoring for the two experimental conditions, sham or active exposure. Sleep latency: Interval from lights out until the onset of stage 2 sleep. Sleep efficiency: Total sleep time as a percentage of total time in bed. Arousal index: Number of wakings or arousals per hour. REM latency: Interval between sleep onset and the onset of the first REM period. NREM Sleep: Percentage of total sleep time. Two-way repeated measures ANOVA (between factor 'order', within factor 'condition', and interaction condition*order) revealed a decrease in REM sleep latency, p=0.020.*

10.3 EMF and Sleep EEG: Effects during the first 30 minutes of sleep[6]

Spectral analysis of the sleep EEG from the first 30 min of the first NREM period was performed on the 3 pre-defined frequency ranges (see section 7.3). A repeated measures ANOVA revealed a significant enhancement of EEG power density in the 11.5–12.25 Hz frequency range following EMF exposure ($F(1,48) = 5.56$, $p = 0.022$) (Figure 17). No significant enhancement was present in the 12.25–13.5 Hz ($F(1,48) = 1.51$, $p = 0.226$) or the 13.5–14 Hz ($F(1,48) = 0.55$, $p = 0.461$) frequency ranges. Effect sizes (partial η^2) were also calculated for the 0–25Hz region and are shown in Figure 18. The largest effect is seen at 11.5 Hz, partial $\eta^2 = 0.105$, which corresponds to a relatively modest effect of the EMF on EEG spectral power in the first NREM period. A comparison between individuals showed that the enhancement of EEG spectral power was not significantly related to age or gender; however, there was more variance (trend-level) found in the female participants ($p = 0.058$), which was presumably due to menstrual phase variation (Driver et al., 1996).

An exploratory analysis was also performed to explore the temporal evolution of the increase in spectral power by dividing the first NREM period into three separate 10 minute segments. The results showed that the enhancement of spectral power in the 11.5 – 12.25 Hz frequency range was not significant until 10 minutes into the first NREM period (1st 10 minutes, $p = 0.396$; 2nd 10 minutes, $p = 0.024$; 3rd 10 minutes, $p = 0.081$).

[6] The analysis of the sleep EEG during the first 30 minutes of NREM sleep has been published by Loughran et al. (2005) in Neuroreport (see appendix G).

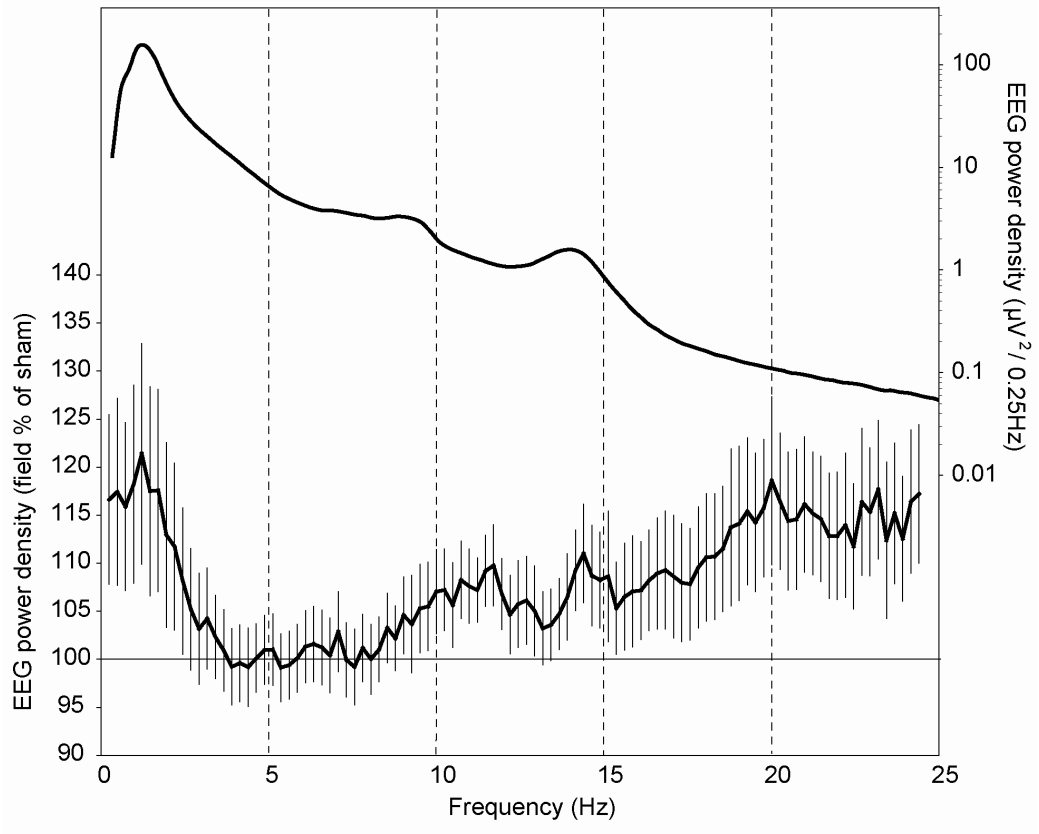

Figure 17 (Loughran et al., 2005). *Mean EEG power density spectrum of the first 30 minutes of the first NREM sleep episode (n = 50 participants). The upper curve is the average spectrum of the sham exposure night for the central derivations (C3 and C4, referenced to linked mastoids). The lower curve represents the average EMF exposure spectrum expressed as a percentage of the corresponding value from the sham condition (mean ± SEM for 0.25 Hz bins, n = 50). A two-way repeated measures ANOVA for the factors condition (sham vs active) and sequence, and their interaction (condition x sequence) was computed, revealing a significant enhancement of power in the 11.5-12.25 Hz range. No significant sequence or interaction effects were present.*

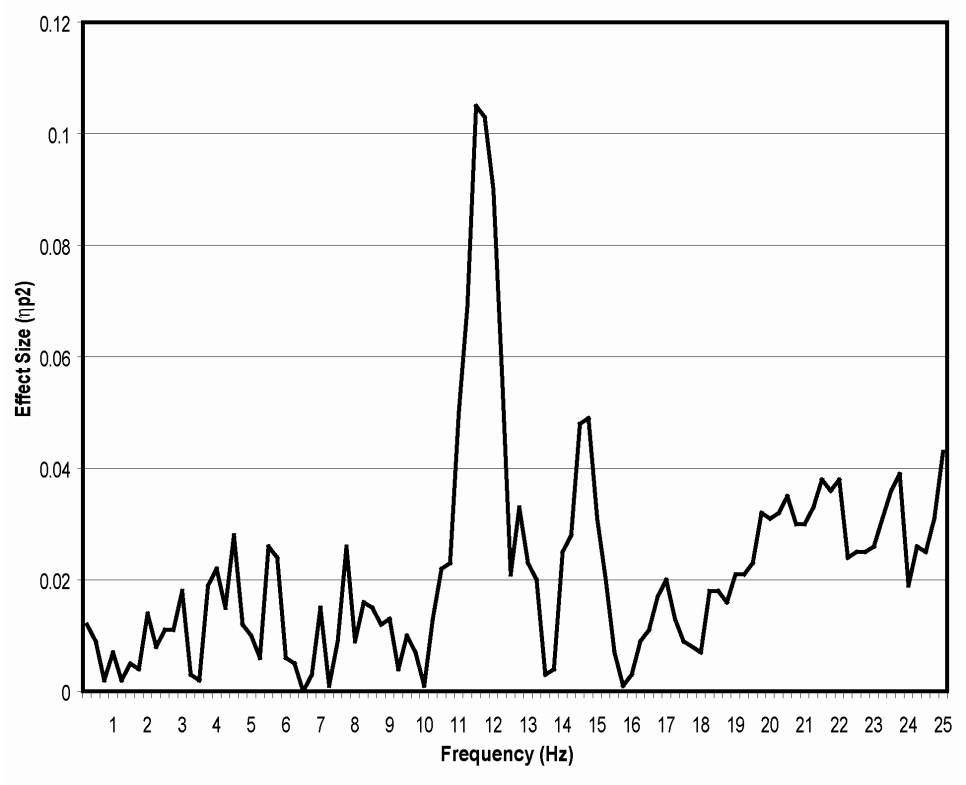

Figure 18 (Loughran et al., 2005). *Effect Sizes of EMF Exposure on First 30 minutes of the first NREM Period. Effect sizes for each 0.25 Hz bin (0-25 Hz) are illustrated and were calculated using the formula* $\eta_p^2 = SS_{effect} / (SS_{effect} + SS_{error})$.

10.4 EMF and Sleep EEG: The time course of the effect

Given that previous research had found differences in the time-course of the effect of mobile phone EMF on the sleep EEG, with the majority of studies finding that the effect was transitory, the time-course of EEG effects was also analysed in the current study. Spectral analysis of the sleep EEG from the first 30 min of the second, third, and fourth NREM periods was performed on the 3 pre-defined frequency ranges mentioned previously (see section 7.3). A repeated measures ANOVA revealed that, as with the first NREM period, there were no significant effects on either the 12.25–13.5 Hz (NREM 1: $F(1,48) = 1.51$, $p = 0.23$; NREM 2: $F(1,45) = 0.56$, $p = 0.46$; NREM 3: F(1,38)

= 1.37, p = 0.25; NREM 4: F(1,16) = 0.11, p = 0.75) or the 13.5–14 Hz (NREM 1: F(1,48) = 0.55, p = 0.46; NREM 2: F(1,45) = 0.00, p = 0.99; NREM 3: F(1,38) = 2.07, p = 0.16; NREM 4: F(1,16) = 2.02, p = 0.17) frequency ranges across the course of the night. Furthermore, although there was a significant enhancement in EEG spectral power in the 11.5 -12.25 Hz frequency range during the first NREM period, this was no longer significant in the second, third, and fourth NREM periods (NREM 2: F(1,45) = 1.55, p = 0.22; NREM 3: F(1,38) = 0.25, p = 0.62; NREM 4: F(1,16) = 0.80, p = 0.38).

10.5 EMF and Sleep EEG: Exploratory Analyses

In addition to the analyses on the three pre-defined frequency bands in both the first NREM period and across NREM periods throughout the night, a number of exploratory analyses were also performed to investigate whether there were any effects at other frequencies, and also whether the EEG during REM sleep was altered due to mobile phone EMF exposure. Each 0.25 Hz frequency bin between 0 and 25 Hz was analysed for each NREM and REM period separately, with the Dubey / Armitage & Parmar method of correction applied for multiple comparisons (see section 7.4).

In the current study, the mean correlation between all of the variables was found to be 0.4298, and considering an alpha level of 0.05 and 800 comparisons, the adjusted significance level using the Dubey / Armitage & Parmar method lowered the critical alpha for each comparison to 0.001. Therefore, for all of the exploratory analyses on the 0 – 25 Hz frequency range for each NREM and REM sleep period, effects were considered to be significant at $p < 0.001$.

The repeated measures ANOVAs revealed that there were no significant effects of the mobile phone exposure on EEG spectral power for any of the 0.25 Hz frequency bins between 0 and 25 Hz for any of the four NREM

periods (Figures 19 – 22). However, there were some trend level enhancements in EEG spectral power in the second and fourth NREM periods, most of which occurred around the 6 - 8 Hz region, and also the 2 – 3 Hz region in the second NREM period (Table 9).

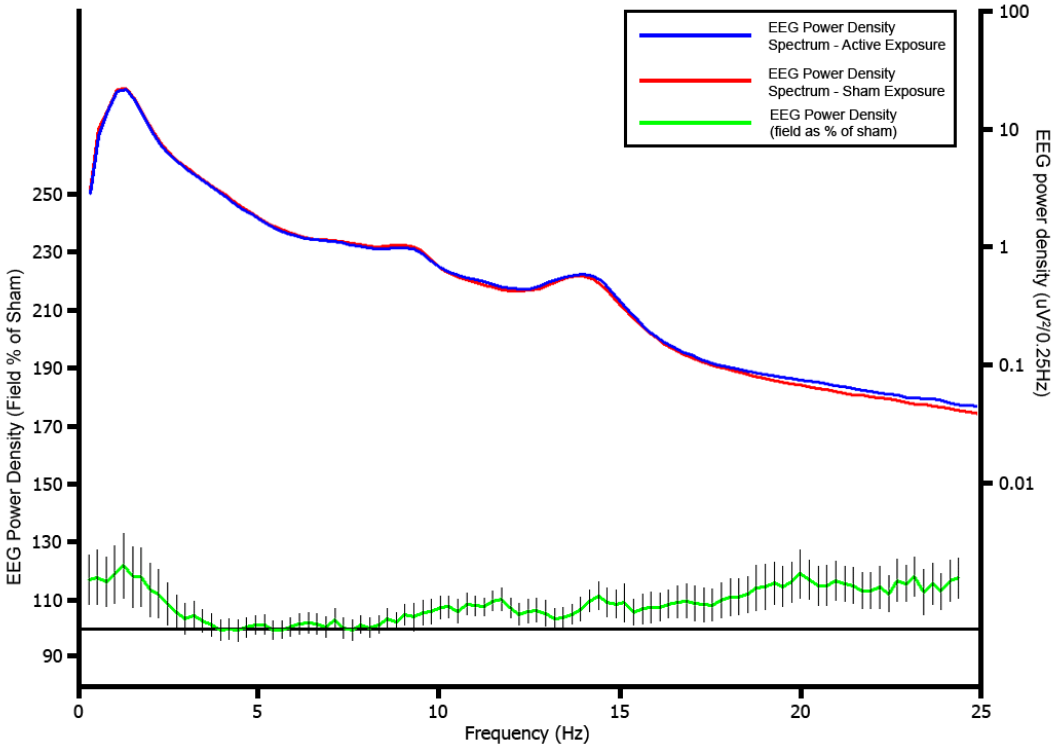

Figure 19. *Mean EEG power density spectrum of the first 30 minutes of the first NREM sleep episode (n = 50 participants). The upper curves represent the spectrum from the sham (red) and active (blue) exposure nights for the central derivations (C3 and C4, referenced to linked mastoids). The lower curve represents the average EMF exposure spectrum expressed as a percentage of the corresponding value from the sham condition (mean ± SEM for 0.25 Hz bins, n = 50).*

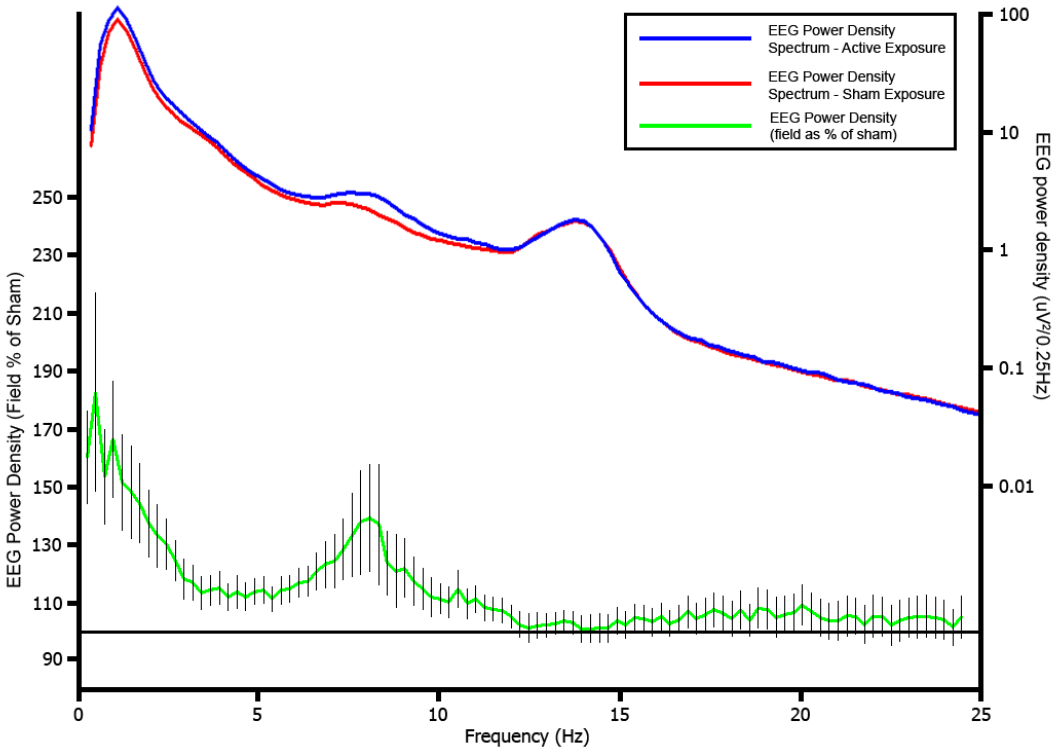

Figure 20. *Mean EEG power density spectrum of the first 30 minutes of the second NREM sleep episode (n = 47 participants). The upper curves represent the spectrum from the sham (red) and active (blue) exposure nights for the central derivations (C3 and C4, referenced to linked mastoids). The lower curve represents the average EMF exposure spectrum expressed as a percentage of the corresponding value from the sham condition (mean ± SEM for 0.25 Hz bins, n = 47).*

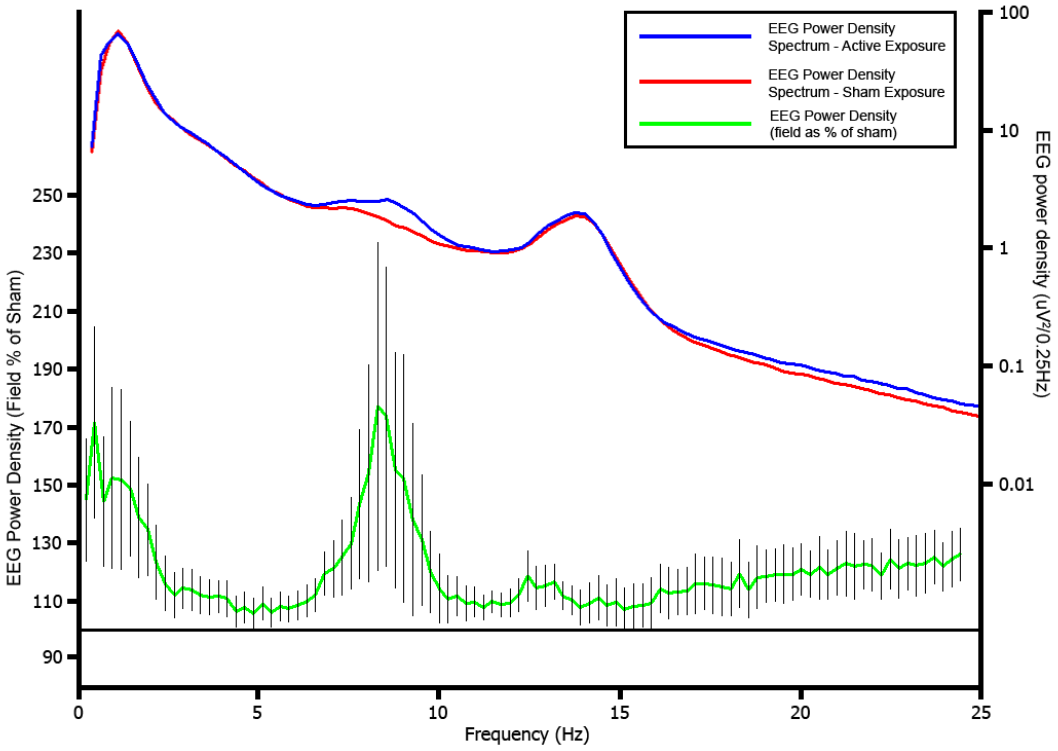

Figure 21. *Mean EEG power density spectrum of the first 30 minutes of the third NREM sleep episode (n = 40 participants). The upper curves represent the spectrum from the sham (red) and active (blue) exposure nights for the central derivations (C3 and C4, referenced to linked mastoids). The lower curve represents the average EMF exposure spectrum expressed as a percentage of the corresponding value from the sham condition (mean ± SEM for 0.25 Hz bins, n = 40).*

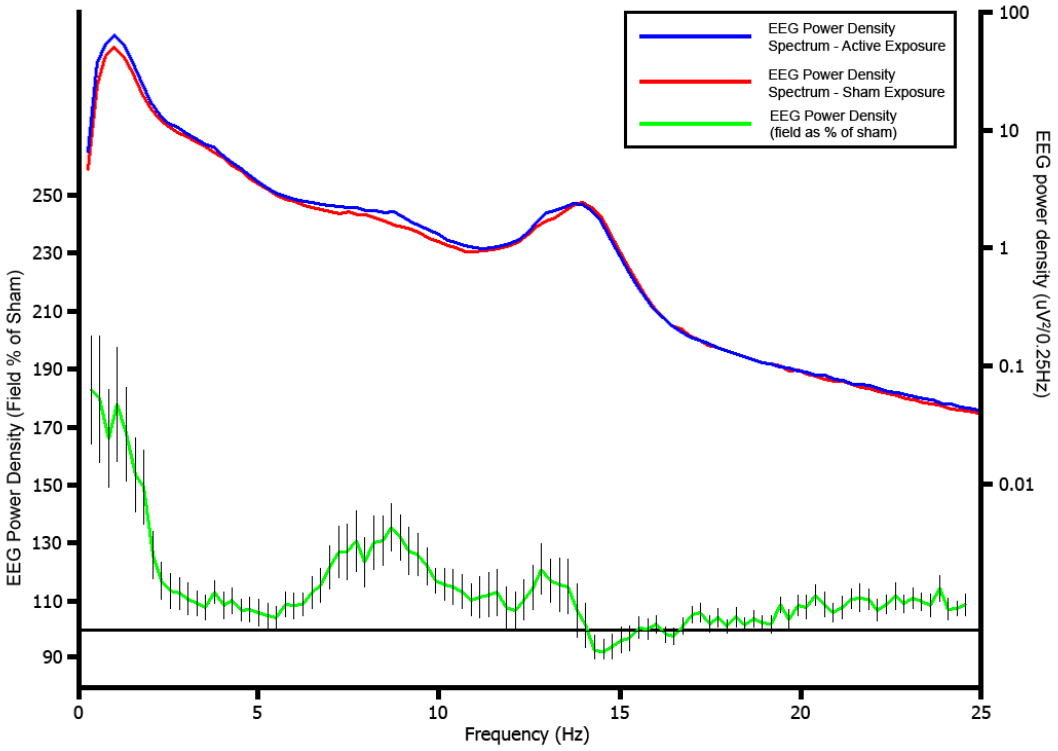

Figure 22. *Mean EEG power density spectrum of the first 30 minutes of the fourth NREM sleep episode (n = 18 participants). The upper curves represent the spectrum from the sham (red) and active (blue) exposure nights for the central derivations (C3 and C4, referenced to linked mastoids). The lower curve represents the average EMF exposure spectrum expressed as a percentage of the corresponding value from the sham condition (mean ± SEM for 0.25 Hz bins, n = 18).*

	Frequency (Hz)	*p*-value
2nd NREM	2.25	0.011
2nd NREM	2.50	0.010
2nd NREM	2.75	0.012
2nd NREM	5.00	0.010
2nd NREM	6.25	0.009
2nd NREM	6.75	0.011
2nd NREM	7.00	0.012
2nd NREM	7.50	0.011
4th NREM	8.75	0.009

Table 9. *Trend level EEG spectral enhancements during NREM sleep following mobile phone exposure.*

In regards to the effects of mobile phone EMF on the REM sleep EEG, repeated measures ANOVAs revealed no significant differences between the exposure conditions, and there were also no trend level effects present (Figures 23 -26).

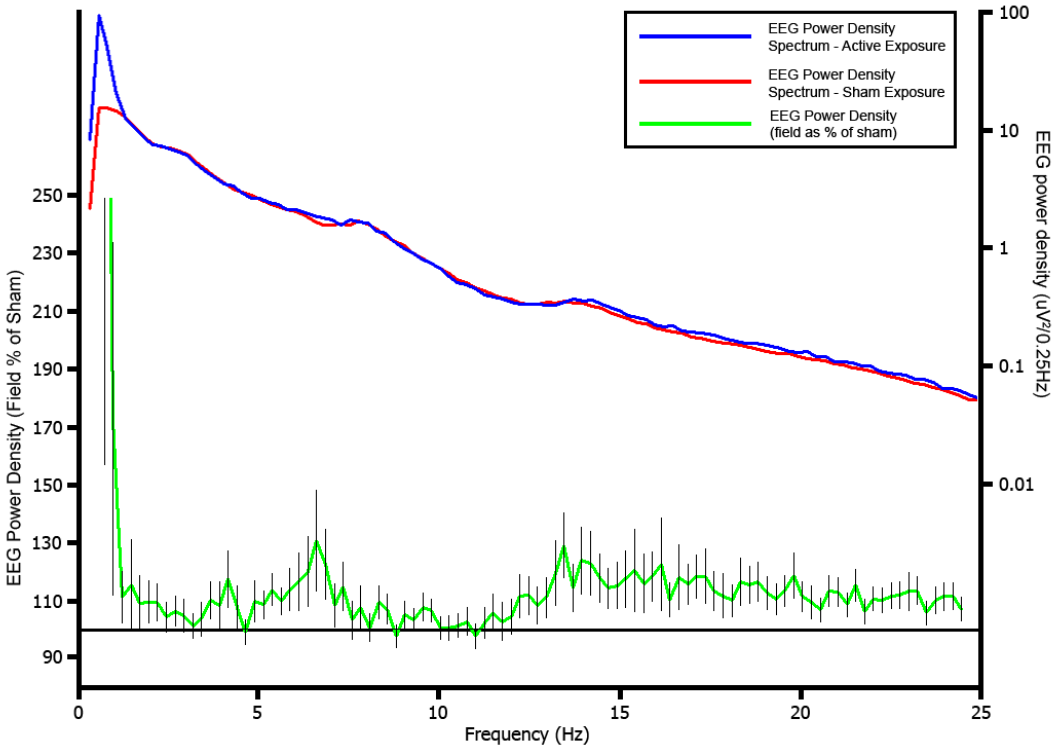

Figure 23. *Mean EEG power density spectrum of the first REM sleep episode (n = 49 participants). The upper curves represent the spectrum from the sham (red) and active (blue) exposure nights for the central derivations (C3 and C4, referenced to linked mastoids). The lower curve represents the average EMF exposure spectrum expressed as a percentage of the corresponding value from the sham condition (mean ± SEM for 0.25 Hz bins, n = 49).*

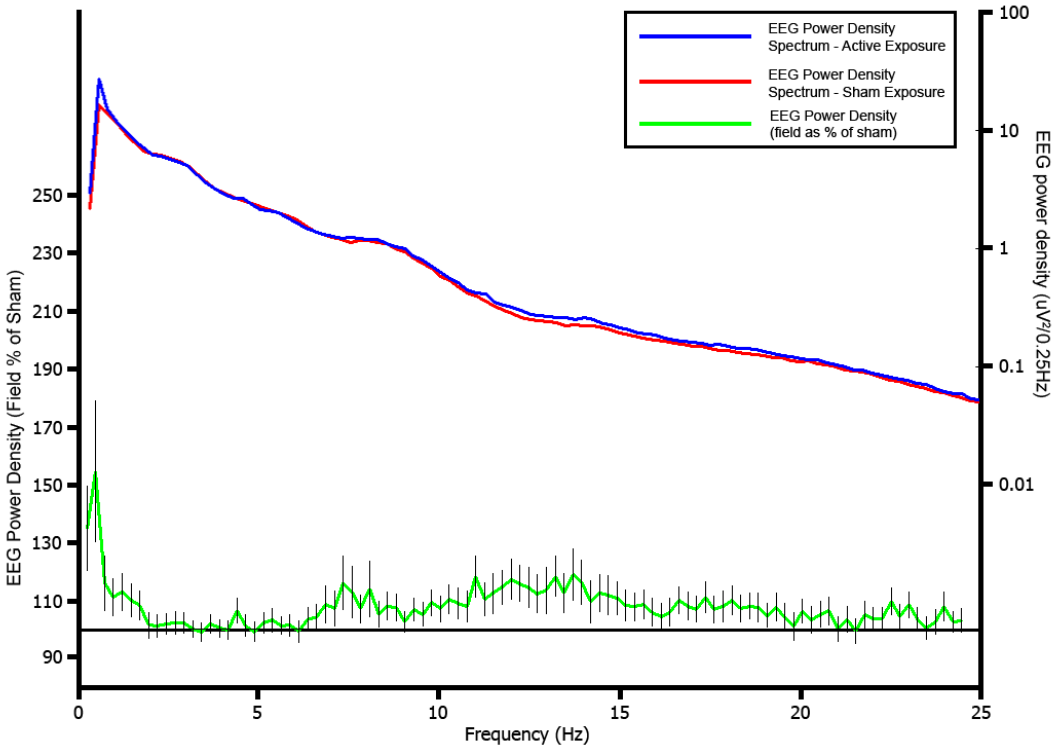

Figure 24. *Mean EEG power density spectrum of the second REM sleep episode (n = 44 participants). The upper curves represent the spectrum from the sham (red) and active (blue) exposure nights for the central derivations (C3 and C4, referenced to linked mastoids). The lower curve represents the average EMF exposure spectrum expressed as a percentage of the corresponding value from the sham condition (mean ± SEM for 0.25 Hz bins, n = 44).*

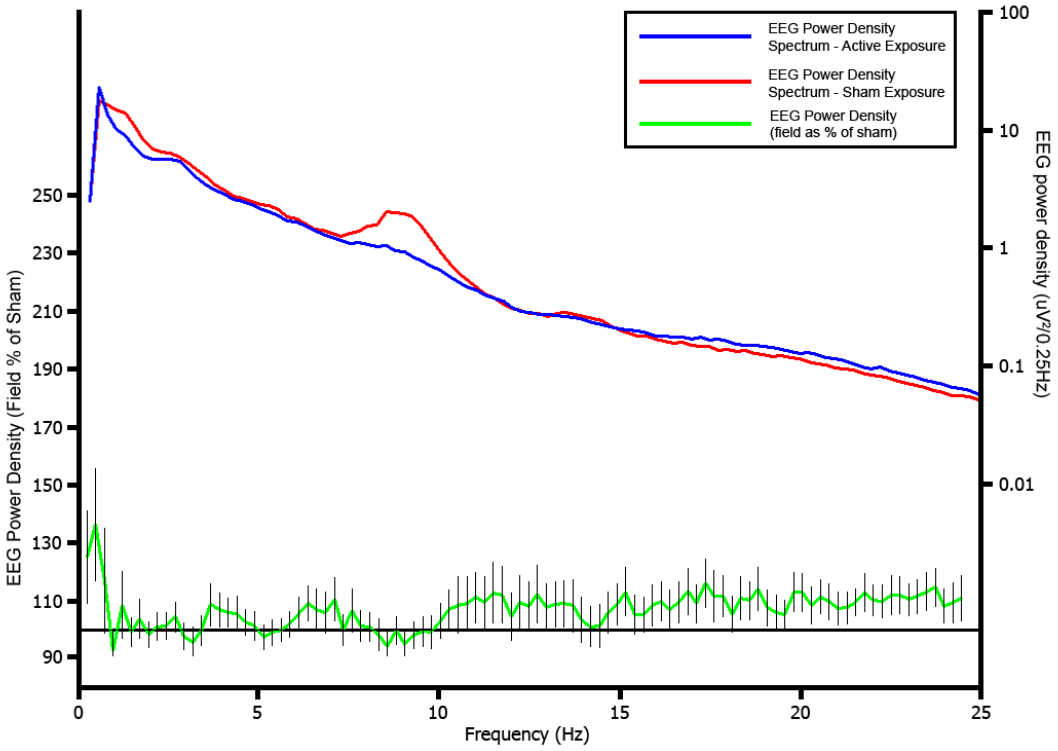

Figure 25. *Mean EEG power density spectrum of the third REM sleep episode (n = 29 participants). The upper curves represent the spectrum from the sham (red) and active (blue) exposure nights for the central derivations (C3 and C4, referenced to linked mastoids). The lower curve represents the average EMF exposure spectrum expressed as a percentage of the corresponding value from the sham condition (mean ± SEM for 0.25 Hz bins, n = 29).*

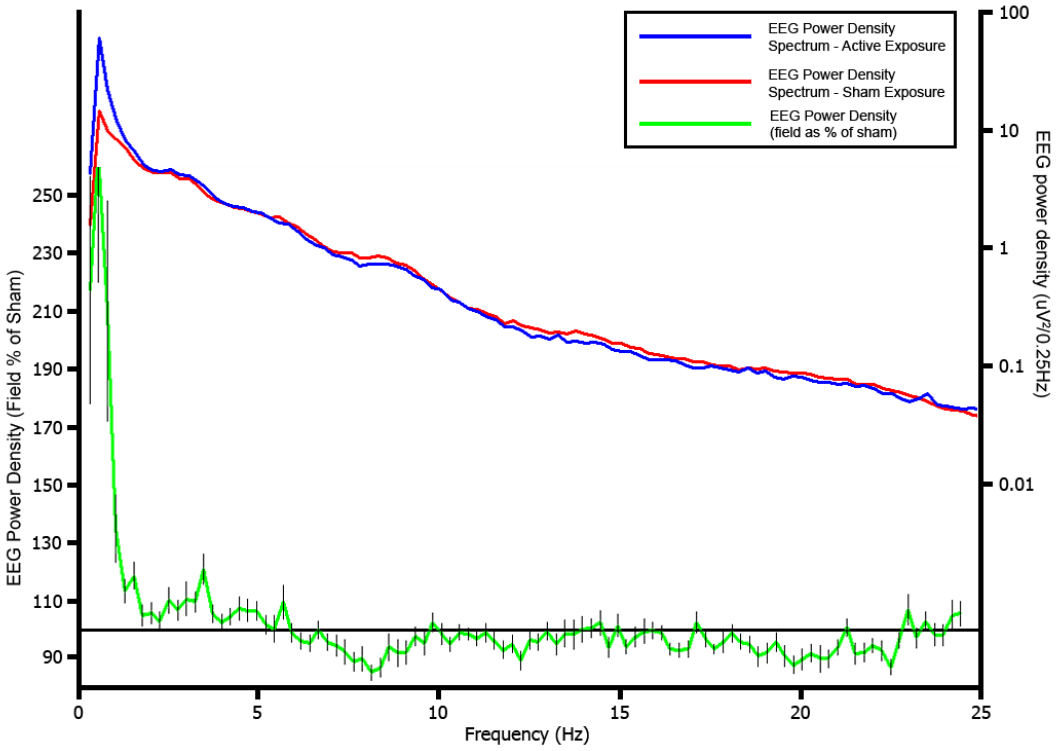

Figure 26. *Mean EEG power density spectrum of the fourth REM sleep episode (n = 9 participants). The upper curves represent the spectrum from the sham (red) and active (blue) exposure nights for the central derivations (C3 and C4, referenced to linked mastoids). The lower curve represents the average EMF exposure spectrum expressed as a percentage of the corresponding value from the sham condition (mean ± SEM for 0.25 Hz bins, n = 9).*

10.6 EMF and Melatonin[7]

All of the statistical analyses on the melatonin data were performed using paired-samples t-tests. There were no significant differences in pre-bedtime or post-bedtime urine volumes either between exposure conditions or between sequences of collection or order of exposure (volume in ml ± SE, Pre-bedtime: sham = 234 ± 17; active = 246 ± 22; Post-bedtime: sham = 344 ± 21; active = 373 ± 25). The amounts of aMT6s in the urine (sample concentration x volume collected) are shown in Table 10. The total aMT6s

[7] The majority of the melatonin analysis has been published by Wood, Loughran, & Stough (2006) in the International Journal of Radiation Biology (see appendix G).

output (± SE) for the two conditions were 14.1 ± 1.1 µg for the active exposure condition and 14.6 ± 1.3 µg for the sham exposure condition. Neither these values nor the separate pre- and post-bedtime values were found to be significantly different from each other.

	aMT6s (µg)	
	Pre-Bedtime	**Post-Bedtime**
Sham	1.9 ± 0.5	12.2 ± 1.0
Active	1.3 ± 0.2	13.3 ± 1.2

Table 10. *Effects of EMF exposure on the melatonin metabolite, aMT6s (Wood, Loughran, & Stough, 2006). Pre-bedtime and post-bedtime amounts (µg) of the melatonin metabolite aMT6s following sham and active exposure (n = 55).*

Because of possible errors in estimation of total volume of urine output, it has been suggested that, since the amount of creatinine output is constant over a given period, the urinary concentration of this substance should be inversely proportional to urine volume produced in that period (Klante et al., 1997). The ratio of aMT6s to creatinine concentrations should therefore be equivalent to the amount of aMT6s. Statistical analysis of the aMT6s concentrations when normalised for creatinine revealed a significant reduction in the active exposure condition pre-bedtime when compared to the pre-bedtime concentrations in the sham exposure condition (Table 11).

Normalized aMT6s Concentration (ng aMT6s/mg Creatinine		
	Pre-Bedtime	**Post-Bedtime**
Sham	7.7 ± 1.3	29.2 ± 2.0
Active	5.6 ± 0.6*	29.4 ± 1.9

Table 11. *Effects of EMF exposure on normalised aMT6s concentrations (Wood, Loughran, & Stough, 2006). *A paired samples t-test (one-tailed) revealed a significant decrease in the normalised aMT6s concentration in the active exposure condition pre-bedtime compared to the pre-bedtime values for the sham exposure condition (p = 0.037) (n = 55).*

Separate analyses of the two exposure orders yielded similar reductions, but failed to reach significance (Mean ± SE; Condition order - sham then active: 7.7 ± 1.7 reduced to 5.6 ± 0.8; Condition order - active then sham: 7.9 ± 2.2 reduced to 5.7 ± 1.0 ng aMT6s/mg Creatinine). The post-bedtime values for the aMT6s concentration were slightly raised for the active exposure condition compared to sham, however this was not significant and the corresponding normalised values were essentially unchanged.

If the exposure to the mobile phone EMF were to cause a delay in melatonin secretion rather than a suppression of melatonin secretion (i.e. effect on onset time), it could be speculated that the ratio of pre-bedtime to post-bedtime aMT6s would be less for the active rather than sham exposure condition. However, there were no significant differences found between the exposure conditions for either the ratios of aMT6s concentrations or their log-transformed values (sham ratio ± SE = 0.46 ± 0.3; active ratio = 0.43 ± 0.3; p = 0.20, one-tailed paired comparison), although the change was in the hypothesised direction. In order to check that this reduction was not a consequence of subjects collecting the first urine sample earlier, by chance,

on the exposure night, the times at which sleep data recording commenced (which was recorded automatically) was checked. The average times were 23:20:56 on the sham exposure night and 23:26:35 on the active exposure night (SE = ± 2 min 40s and 3 min 40 s respectively). Thus, if anything, the first urine collection occurred later on the active exposure night compared to the sham exposure night.

A more detailed breakdown of individual changes in the pre-bedtime normalised aMT6s is shown in Figure 27. Clearly, there were four individuals (3 female, 1 male) with substantial reductions, with the remaining 51 participants being normally distributed around zero. If these four individuals are considered as being outliers and therefore eliminated from the analysis, the change in pre-bedtime normalised aMT6s concentrations becomes non-significant ($p = 0.45$). These 4 individuals showed no common characteristics in responses to the demographics/electrosensitivity questionnaires and as shown in Figure 28, no extreme differences in bedtimes between the two exposure conditions. Further, the actual bedtimes were close to the mean values reported of the entire sample reported previously.

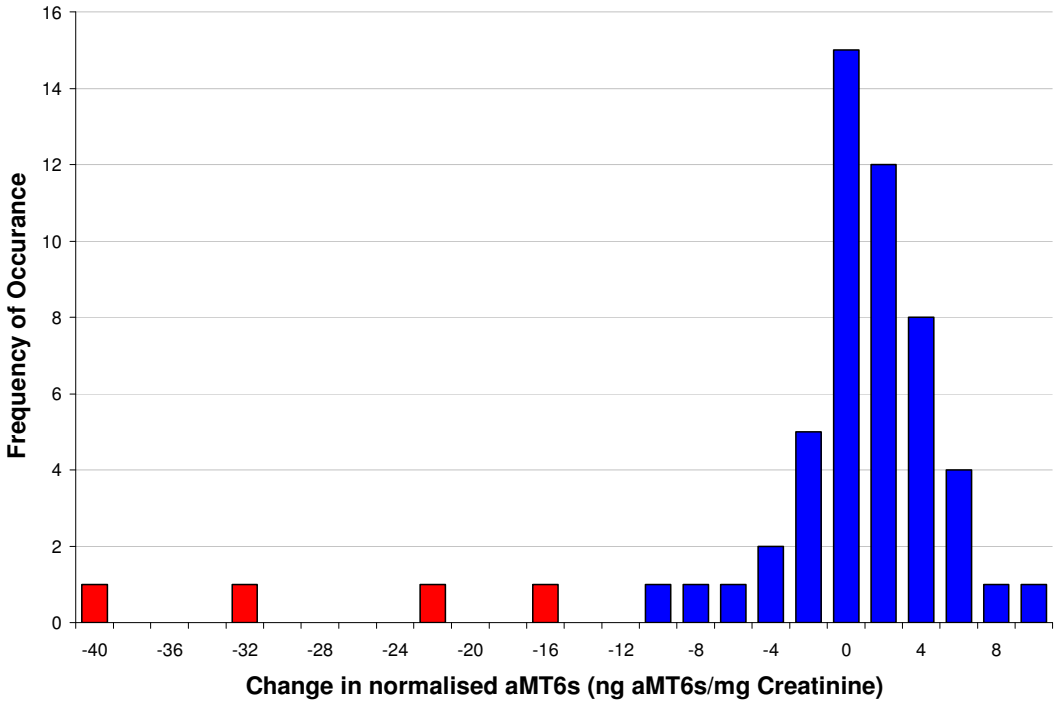

Figure 27 (Wood, Loughran, & Stough, 2006). *Individual changes in pre-bedtime normalized aMT6s on the two exposure nights (n = 55). A paired samples T-test (one-tailed) revealed a significant decrease in the normalised aMT6s concentration in the active exposure condition pre-bedtime compared to the pre-bedtime values for the sham exposure condition (p = 0.037). However, four individuals were identified as outliers (shown in red), and when removed from the analysis, the change in normalised aMT6s was no longer significant (p = 0.45).*

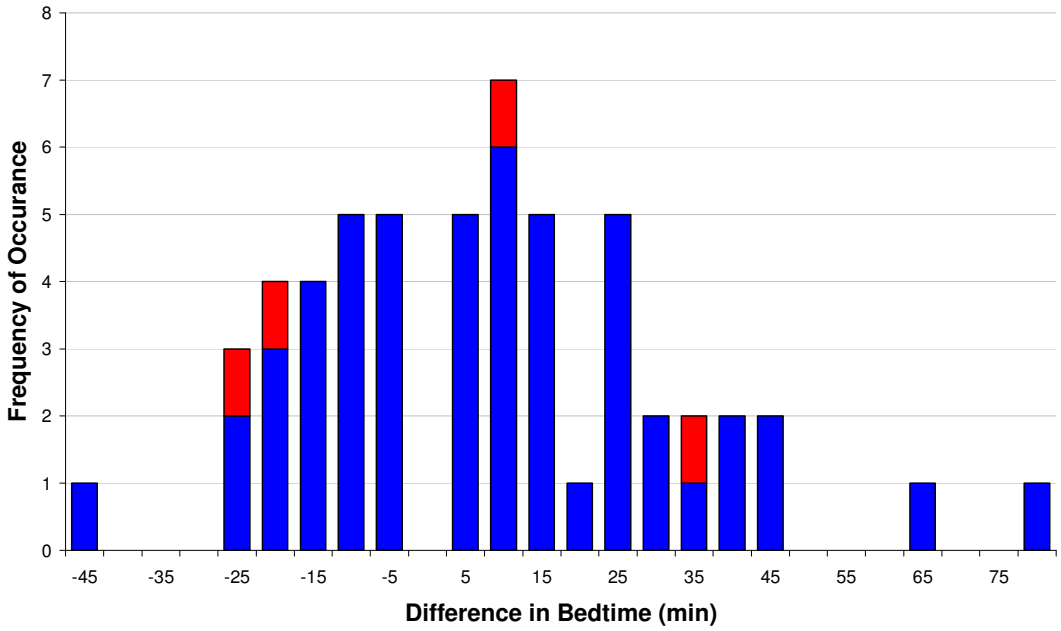

Figure 28 (Wood, Loughran, & Stough, 2006). *Histogram of differences in bedtime (time of commencement of polysomnographic recording in minutes) on the two exposure nights when urine was collected. Differences for the four participants who were identified as outliers are shown as the red bars.*

Additionally, in the analysis of sleep architecture (see section 8.1.2), 5 participants were identified as suffering from some form of respiratory related sleep disturbance. If these individuals were excluded from the melatonin analysis, the reduction in pre-bedtime normalised aMT6s is still significant ($p = 0.047$). None of the four participants that were considered as being outliers suffered from respiratory related sleep disturbances, and therefore were not the same participants that were excluded in the analysis of sleep architecture.

However, while the use of parametric statistics (such as the t-test) is generally very robust, having considerable power to detect differences in population parameters, they also involve assumptions about the distribution of the population from which the data were randomly sampled. In particular,

a repeated measures t-test assumes that the data is normally distributed and that the variances of the distributions being compared are equal. In light of this, and considering that the melatonin data was not normally distributed (with four clear outliers present in the population sample), the assumptions about the population distribution required for a t-test were not met and therefore it would be more appropriate to employ a non-parametric technique to analyse the creatine-adjusted melatonin data, as non-parametric statistics do not require the assumptions of normal distribution or equality of variance in the data.

Therefore, a Wilcoxon signed-rank test, which is the non-parametric alternative to the repeated measures t-test, was subsequently used to more accurately analyse the effects of mobile phone exposure on creatinine-adjusted melatonin secretion. The Wilcoxon signed-rank test indicated that there was no difference between the active and sham exposure conditions for either the pre-bedtime ($z = -0.0846$, $p = 0.397$) or post-bedtime ($z = -0.184$, $p = 0.854$) values for aMT6s concentration.

10.7 Summary of Results

The current study showed that 30 minutes of mobile phone EMF exposure prior to night-time sleep lead to a decrease in REM sleep latency by 17 minutes compared to the sham exposure condition. Other conventional sleep parameters, such as total sleep time, sleep onset latency, percentage of stage 1, 2 and slow wave sleep, arousal indices, sleep efficiency, and the percentage of NREM and REM sleep showed no alteration between exposure conditions.

In regards to the sleep EEG, the present results suggested that mobile phone EMF exposure causes an enhancement in EEG spectral power in the 11.5 – 12.25 Hz frequency range, with the largest effect being seen at 11.5 Hz. This

enhancement of EEG spectral power was seen in the first 30 minutes of the first NREM sleep period, however, there were no significant changes in EEG found for this frequency range or any other frequencies in any of the subsequent NREM periods. Furthermore, the current results did not show any evidence of a change in EEG spectral power during REM sleep following mobile phone EMF exposure.

Finally, analysis regarding melatonin production and output suggested that, overall, there was no influence of mobile phone EMF exposure prior to sleep on subsequent melatonin production.

Possible mechanisms for the significant mobile phone-induced effects found, implications of the current results, and possible limitations of the current study are discussed in chapter 11.

Chapter 11: Discussion & Conclusions

This chapter summarises the main results of the current study (see Table 12 for summary of current results) and provides conclusions regarding the effect of GSM mobile phone exposure on conventional sleep parameters, spectral analysis of the sleep EEG, and melatonin production and secretion. Possible mechanisms for the significant mobile phone-induced effects found and the implications of the current results are discussed. Possible limitations of the current study are also discussed, and implications and recommendations for future research are highlighted.

11.1 Conventional Sleep Parameters

Overall, the present study found that 30 minutes of exposure to the RF EMF emitted by a mobile phone, prior to sleep, decreased REM sleep latency. This is inconsistent with all of the previous research on the effects of RF EMF on conventional sleep parameters, and is therefore the first study to report a mobile phone-induced decrease in REM latency. Due to this inconsistency with previous literature, no conclusions can be made regarding this influence of mobile phone exposure on REM latency, with further studies also required in order to verify this effect.

Unlike previous research that has reported an overall suppressive effect of EMF exposure on REM sleep (Mann and Roschke, 1996; Wagner et al., 1998), the current study found no differences in the percentage or duration of REM sleep between the active and the sham mobile phone exposure conditions, and it is the first study to find that exposure to RF EMF prior to sleep decreased REM sleep latency compared to the sham exposure condition. No influence of EMF exposure on any of the other sleep variables,

such as total sleep time, sleep latency, and slow wave sleep, was found, which is consistent with the majority of previous research that has also failed to identify any differences in conventional sleep parameters (see Table 8). Therefore, the only inconsistent result of the current study is in regards to REM sleep parameters. Given that the suppression of REM sleep that was originally reported by Mann and Roschke (1996) has not been replicated in other subsequent studies, and taking into account the limitations in exposure parameters in that study, namely exposure duration and dosimetry limitations (see section 6.3) which have been addressed in the current study, the present results should be more reliable and therefore suggest that REM sleep is not suppressed by normal mobile phone use.

Interestingly, the decrease in REM sleep latency observed in the current study would also not be consistent with a suppression of REM sleep. The significance of such a decrease in REM latency is difficult to determine, although a reduction in REM sleep onset has often been seen in unmedicated depressed patients and also other psychopathological conditions (Benca et al., 1992; Riemann et al., 2001). Other common sleep disturbances observed in depression, such as reductions in slow wave sleep, prolongation of the first REM period, and increases in REM density, however, were not seen in the current study following mobile phone EMF exposure. A decrease in REM sleep latency could also suggest initial alterations to the ultradian rhythm of the NREM/REM sleep cycle (Roth, 2004).

One possible mechanism behind the observed decrease in REM sleep latency could involve innervation of cholinergic neurons, as there is considerable evidence that suggests that cholinergic activity plays an important role in the regulation of behavioural state, particularly in the initiation and maintenance of REM sleep (Shiromani et al., 1987; Pace-Schott and Hobson, 2002; Espana and Scammell, 2004).

It should also be noted that, although a decrease in REM sleep latency by 17 minutes was seen in the current study following mobile phone exposure (compared to the sham exposure condition), the REM latency in the active exposure condition of 90 minutes was still within what would be considered normal timing of the human sleep cycle (see section 2.1), and therefore even if true, does not likely represent a detrimental effect of the mobile phone. However, as a decrease in REM sleep latency following mobile phone EMF exposure has not been reported previously, this effect needs to be replicated before any firm conclusions can be drawn regarding EMF induced effects on REM sleep or any health consequences of this effect.

11.2 The Sleep EEG: NREM Sleep

The investigation into the effects of mobile phone emissions on the sleep EEG revealed that 30 minutes of exposure to a GSM digital mobile phone, prior to a full night-time sleep episode, affects the subsequent EEG during sleep. The increase in EEG spectral power was present in the first 30 minutes of NREM sleep and was enhanced in the frequency range corresponding to slow sleep spindles. Enhancement of NREM sleep EEG power induced by RF EMF exposure in the frequency ranges largely determined by slow and fast sleep spindles has also been reported in a number of previous studies (Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003), and although the specific frequencies at which EEG power was enhanced has been somewhat inconsistent, we have shown that exposure to mobile phone RF EMF emissions can induce changes in the 11.5 – 12.25 Hz frequency range in the first NREM sleep period. Interestingly, a breakdown of the first 30 minutes of NREM sleep revealed that the enhancement in EEG spectral power was significant 10 minutes into the NREM sleep period, but after 20 minutes this enhancement was no longer significant. This finding suggests that mobile phone EMF exposure leads to changes in brain activity even after the phone has been turned off,

and is consistent with several other studies on the awake and sleep EEG that have also reported delayed effects post-exposure (Huber et al., 2002; Huber et al., 2003; Curcio et al., 2005; see Cook et al., 2006 for review).

The results of the exploratory analyses on the time-course of EEG spectral power enhancements during NREM sleep showed that although there was a significant enhancement in the 11.5 – 12.25 Hz frequency range during the first NREM period, there were no significant enhancements in the spindle frequency range or any other frequency ranges found following mobile phone exposure for any of the subsequent NREM sleep periods. This finding is consistent with the majority of past research (Mann and Roschke, 1996; Wagner et al., 1998; Borbely et al., 1999; Huber et al., 2000; Wagner et al., 2000; Huber et al., 2003) and would suggest that, although effects can be delayed or still present up to an hour or so after the exposure has ceased, enhancements in EEG power are still largely transitory and do not linger throughout the night. Therefore, the results of the current study not only showed that 30 minutes of exposure to mobile phone EMF is sufficient to induce changes in the sleep EEG during the initial part of sleep, but also confirmed that these changes in EEG are somewhat transitory and restricted to the first NREM period, which is consistent with a number of previous findings (Borbely et al., 1999; Huber et al., 2000; Huber et al., 2003).

The significance of an enhancement of EEG spectral power in the sleep spindle frequency range during the initial part of sleep remains unknown, however, as there were no detrimental effects of mobile phone EMF on conventional sleep parameters observed in the current study, it would be premature to draw any conclusions regarding health consequences related to this change in EEG, particularly as the overall quality of sleep derived from the variables measured was not changed. However, given that previous studies have consistently shown alterations in the sleep spindle frequency range following exposure, and that cognitive functioning, such as memory consolidation and learning, has been associated with spindle and slow wave

activity (Gais et al., 2002; Gais and Born, 2004; Bodizs et al., 2005; Stickgold, 2005; Walker and Stickgold, 2006), this may suggest that a consequence of a mobile phone induced change in sleep spindle frequencies may be changes in cognitive functioning, either relating to the memory consolidation process itself, or to subsequent cognition the next morning.

It has also been suggested previously that subcortical regions, such as the thalamus, may be more sensitive to high frequency pulsed EMF than other structures of the brain, and because spindle oscillations are generated in the thalamus (Steriade et al., 1993), mobile phone EMF emissions may be stimulating cortical neurons to induce alterations in sleep spindle activity (Huber et al., 2003). This supposition is also supported by the lack of hemispheric asymmetry in the sleep EEG enhancements that have been found in previous studies, as subcortical structures, such as the thalamus, have bilateral cortical projections and, therefore, if EMF exposure is influencing these subcortical structures this could be a possible explanation for the similar hemispheric effects of RF EMF exposure that have been seen regardless of which hemisphere received the exposure. Although speculative, it may be that these observations could also suggest the presence of a downstream effect (that is, an indirect effect of the mobile phone RF EMF on subcortical structures), with the mobile phone exposure affecting the activity of neurotransmitters that innervate the thalamo-cortical networks that are proposed to be sensitive to the RF EMF emitted by mobile phones. Again, this effect could involve the innervation of cholinergic neurons, specifically at sites such as the pedunculopontine and laterodorsal tegmental nuclei that send direct cholinergic projections to the reticular thalamic nucleus (which is thought to play a key role in the regulation of thalamo-cortical transmission and to be the initial site in the sleep spindle generating network) (Steriade et al., 1993)

Furthermore, the transitory nature of the effect and the absence of any changes in EEG spectral power later in the sleep episode could also suggest the presence of an adaptation mechanism which leads to a return of brain activity to normal levels and patterns after the initial NREM period. Mann and Roschke (2004) have suggested that the idea of an adaptation mechanism is also in accordance with previously reported neuroendocrine alterations from EMF exposure (Mann et al., 1998), with a transient elevation in cortisol serum levels reported during the first hour of EMF exposure around sleep onset, which was followed by a rapid adaptation of the system during the subsequent sleep period. However, these changes in cortisol levels observed by Mann and Roschke (1998) have been questioned by a subsequent study in which no alterations of cortisol levels were found in relation to EMF exposure (Radon et al., 2001), although measurement techniques differed between the two studies (serum vs. salivary cortisol levels) which may help to explain the different findings. Nevertheless, confirmation of a transient change in cortisol levels, and investigations into whether changes in cortisol follow a similar pattern to EMF induced changes in sleep EEG, is required before any conclusions or interpretations can be made in regards to adaptation mechanisms to EMF exposure.

11.3 The Sleep EEG: REM Sleep

Analysis of the sleep EEG during REM sleep did not reveal any significant alterations in EEG spectral power induced by the mobile phone EMF exposure. This finding is consistent with the majority of previous studies that have reported that mobile phone-induced changes in EEG power appear to be restricted to NREM sleep (Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003). The current results are inconsistent with the early study by Mann and Roschke (Mann and Roschke, 1996), who reported an increase in EEG power mainly in the alpha frequency range during REM sleep, however, given that changes in EEG during REM sleep were not able

to be replicated by the same group (Wagner et al., 1998; Wagner et al., 2000), and have not been found in any other subsequent studies from other laboratories (Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003; Hinrichs et al., 2005), the current results therefore can confirm that there is no influence of mobile phone EMF on the EEG during REM sleep.

One possible explanation for the lack of effects on the REM sleep EEG could be that the initiation of REM sleep, which is physiologically quite distinct from NREM sleep, may 'turn off' the changes induced in the NREM sleep EEG during the process of transition into the REM sleep state. However, more likely explanations for why the EEG during REM sleep is not altered is the lack of sleep spindle activity during REM sleep, or that the enhancement of EEG power does not last long enough and is therefore no longer present at the time of transition between the first NREM and REM sleep periods. The current results support the transient nature of EMF-induced changes in EEG power, showing that 90 minutes into sleep, when the first REM period occurred on average in the exposure condition, there was no longer any effects of the mobile phone EMF on the EEG spectral power evident. This is also supported by the results reported by Borbely et al., (1999), in which exposures applied throughout the night did not lead to an extended enhancement in EEG spectral power over the course of the night, or to the presence of an effect during REM sleep. Therefore, regardless of whether the exposure occurs prior to sleep or during sleep, a number of past studies have reported that the mobile phone-induced effects are restricted to the initial part of the night (Borbely et al., 1999; Huber et al., 2000; Huber et al., 2003), supporting the transient nature of this effect. However, one recent study reported that enhancements in EEG spectral power occurred throughout the night during the NREM sleep periods after only 30 minutes of RF EMF exposure (Huber et al., 2002), which is inconsistent with most previous research and the current results, and leads to limitations in concluding that the transient nature of the mobile phone-induced effect is the

main reason behind the lack of effects reported on the REM sleep EEG. Conversely, the current results would also support the hypothesis that spindle generating mechanisms or sleep spindles are the likely candidates for the EMF-induced effects on EEG power during NREM sleep, as sleep spindles are generally not present during REM sleep. The strongest evidence supporting an effect on sleep spindles or spindle generating mechanisms is that the majority of previous studies have reported effects that are restricted to the EEG during NREM sleep (Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003), and regardless of whether the enhancement in EEG was observed during the initial part of sleep or throughout the entire night, the effect was only observed in the NREM sleep stages (Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003). Furthermore, the EEG enhancements reported have all roughly been within the frequency bands associated with slow and fast sleep spindles, further supporting the view that mobile phone exposure is affecting sleep spindle activity, because if spindle activity is indeed altered by mobile phone EMF and behind the changes in EEG that have been reported in previous studies and the current study, similar effects to those that are seen during NREM sleep would not be expected during REM sleep when spindles are generally not present. Although both explanations are possible, the transient nature of the effect on the EEG has been somewhat less consistent, and therefore the distinction between NREM and REM sleep periods, namely the presence of sleep spindles, would seem the most feasible explanation for the absence of an influence of mobile phone exposure on the sleep EEG during REM sleep at present.

11.4 Recent Research

Subsequent to the completion of the current study, a research group in Germany reported results from a study that was designed to investigate the effects of short- and long- term pulsed RF EMF on night sleep and cognitive

functions in healthy subjects (Fritzer et al., 2007). The study consisted of 20 healthy male participants, 10 who received EMF exposure and 10 who received sham exposure in a between-subjects study design. All participants spent 8 consecutive nights in a sleep laboratory in which the first night acted as an adaptation night, the second night was a reference or baseline night, and during the following 6 nights the participants were exposed to the RF EMF throughout the entire sleep episode. The baseline night (night 2) was used as a reference level, with nights 3 and 8 defined as the short- and long-term exposure conditions for analysis, respectively. On these three nights the participants were also required to complete a neuropsychological test battery that examined components of attention, learning, and memory. The exposure consisted of 3 dipole antennas that were placed at a distance of 30cm from the participants' head and emitted a 900 MHz signal (pulsed at 217 Hz), resulting in a relatively homogenous SAR of approximately 1 W/kg in the human head.

The results of the study indicated that there were no significant effects of RF EMF exposure on conventional sleep parameters or cognitive functioning, regardless of whether the exposure was considered short-term (first exposure night) or long-term (6^{th} exposure night). It was also reported that spectral analysis of the sleep EEG revealed no significant changes between the baseline/reference night and the short- and long- term exposure nights, for both the NREM and REM sleep periods. From these results the authors concluded that there is no significant impact of the EMF emitted by mobile phones on sleep behaviour, the power spectra of the sleep EEG, or on cognitive functioning, which is in direct contrast to both the results of the current thesis and the majority of previous studies which have observed effects on the sleep EEG related to mobile phone exposure (Mann and Roschke, 1996; Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003).

There are a number of potential reasons why the study by Fritzer et al. (2007) failed to confirm a mobile phone-induced change in sleep EEG activity, particularly in relation to the study design. The Fritzer et al. (2007) study used a between-subjects design, with a particularly small sample size (10 per group), which differs significantly from all of the previous studies (including the current thesis) which used within-subjects (also referred to as repeated measures) study designs. The use of a between-subjects design to investigate the effects of RF EMF on human sleep and the sleep EEG could be considered inadequate for a number of reasons. Within-subjects study designs are generally considered to be more sensitive than between-subjects designs (that is, they are more likely to be able to detect differences in exposure conditions if a difference does in fact exist), and given that previous effects of RF EMF exposure on the sleep EEG have been of a small magnitude, a between-subjects study design with a small sample size as employed by Fritzer et al. (2007) would tend to be less sensitive than the previous research using within-subjects designs, and therefore less likely to have been able to detect an effect.

Similarly, in between-subjects designs there is more error variance due to individual differences (and subsequently less statistical power), and given that it is widely accepted that there can be quite large differences in EEG activity between individuals, with evidence suggesting the presence of an individual alpha frequency in the awake EEG (Klimesch, 1999) and a pattern of EEG power distribution in NREM sleep that is characteristic for a particular individual (Finelli et al., 2000), a between-subjects design would be a particularly poor choice for investigating mobile phone-induced effects on the sleep EEG.

Additionally, the study by Fritzer et al. (2007) failed to improve on previous limitations regarding exposure design (see section 6.3), by using an antenna that exposed the entire head at levels much higher than would be expected from a mobile phone handset, for an unrealistic duration (8-hours throughout

the entire sleep episode). Therefore, the authors comment that the exposure design used provides a realistic simulation of a mobile phone is also inaccurate (see section 9.2 for discussion on exposure set-ups), and therefore the results cannot be generalised to mobile phone use.

Due to the significant limitations that have been identified, particularly the inappropriate study design used and the small number of participants included in the study, the results of Fritzer et al. (2007) cannot be considered as an accurate representation of RF bioeffects related to mobile phone use on human sleep and the EEG. Furthermore, it should be noted that the results reported by Fritzer et al. (2007) cannot be viewed as a rebuttal of the results in the current thesis, due to the significant limitations in the Fritzer et al. (2007) study, and therefore does not affect the discussion and conclusions drawn regarding the results of the current thesis.

11.5 Melatonin Secretion

The overall results of the present study suggest that overnight melatonin secretion, as measured by the amount of urinary melatonin metabolite aMT6s, is unaffected by exposure to a mobile phone for 30 minutes immediately prior to sleep. However, a significant reduction in aMT6s concentration relative to creatinine concentrations was found in the active exposure condition for the pre-bedtime urine samples. Although further analyses showed that there was no influence of condition order (active vs. sham first) or the time at which urine was collected, a more detailed breakdown of the data revealed that there were four participants with substantial reductions in aMT6s concentrations, and when these four individuals were removed from the analysis, there was no longer a significant difference in pre-bedtime aMT6s concentrations between the active and sham exposure conditions. The normalised aMT6s values for these four participants in the sham condition were very high compared to the rest of the

study population, which could indicate that the natural melatonin onset time was earlier in these individuals and that the exposure affected them because it occurred during a sensitive period. However, given the relatively small numbers tested and the possible limitations related to the melatonin analysis (see section 5.3), experimental artefact cannot be ruled out. Furthermore, when the melatonin data was subsequently compared using a more appropriate nonparametric statistical test which included the entire study population, there was also no longer a significant reduction in the creatine-adjusted aMT6s concentrations, which would suggest that there was no influence of the mobile phone RF EMF on melatonin production or secretion.

However, if the reduction found in the creatinine-adjusted aMT6s is indeed a real effect, one possible explanation might be a delay in melatonin onset and that the relatively small number of individuals 'responding' is a function of the timing of exposure relative to melatonin onset on a particular night. For example, the exposure could have been applied during a sensitive period in the circadian melatonin cycle in a small number of participants', possibly delaying the onset of melatonin secretion, whereas exposure outside of this sensitive melatonin onset period may have little or no effect on melatonin onset time. Another possibility is that the rate of breakdown from melatonin to aMT6s is being reduced by the mobile phone exposure, although this explanation would not account for why only a small subset of the study population may have been affected by the mobile phone exposure. Given that a reduction in aMT6s concentrations was only found in a very small subset of the study population and was not significant when stronger nonparametric statistics were applied, and also that previous research has not consistently found mobile phone-related reductions in melatonin or the principal melatonin metabolite, independent verification of the influence of mobile phone emissions on human melatonin secretion and onset time is required before any conclusions can be made regrading the melatonin results of the current study.

Measure	Description of result
Conventional Sleep Parameters	1. Decrease in REM sleep latency (17 mins) 2. No change in total sleep time, sleep onset latency, arousal index, sleep efficiency, stage 1 %, stage 2 %, slow-wave sleep %, NREM sleep, and REM sleep
Sleep EEG	1. Significant enhancement 11.5 – 12.25 Hz frequency range in the first NREM period 2. No effect during NREM periods 2, 3, or 4 3. No effect on during REM sleep
Melatonin	1. No overall effect on the secretion of aMT6s

Table 12. *Summary of results from the current study.*

11.6 Possible RF Bioeffect Mechanisms

Although the current study and previous studies have shown that mobile phone RF EMF can lead to biological effects, particularly changes in the EEG during both sleep and waking, the mechanisms behind this interaction have not yet been established. Interaction between RF EMF and biological tissue can occur through either thermal or nonthermal mechanisms (Challis, 2005). As described previously (see section 4.1), thermal effects are those that are related to the generation of heat in biological tissue which in turn can lead to changes in biological functioning, especially when induced tissue heating is increased by more than 1°C, exceeding the thermoregulatory capacity of the human body (Habash, 2002). However, as the low intensity emissions from mobile phone handsets are not sufficient to cause significant heating of biological tissue, any effects observed are likely due to nonthermal mechanisms, which are those that are not directly associated with

temperature changes but to some other change produced in the tissue by the RF electric or magnetic field (Challis, 2005).

A number of theories on possible nonthermal mechanisms have been reported over recent years, particularly in relation to the possible excitation of nerve cells and the pulsing and demodulation of mobile phone carrier signals. In regards to the excitability of nerve cells, changes in calcium binding to cell receptor proteins has been the most common theory (Adey, 1981; Blackman et al., 1988; Chiabrera et al., 2000). In particular, a more recent study by Chiabrera et al. (2000) reported that RF electric fields below guideline values could in fact induce changes in the binding of ligands such as calcium. Given that there is some support for a calcium efflux induced by low intensity RF EMF, it has been speculated by Hamblin and Wood (2003) that *in vivo*, if enhancements in calcium efflux occur, this would in turn lead to a hypercalcaemic environment, which has also been reported previously to correlate with EEG activity including within the alpha frequency range. Therefore, it could be speculated that excitation of nerve cells by mobile phone emissions could lead to changes in calcium binding which in turn may lead to changes in EEG activity, providing one possible explanation for the mechanism behind the enhanced alpha and sleep spindle EEG activity reported in the current study.

Another proposed nonthermal mechanism that has received attention in recent years is related to the pulsed modulation of the carrier signal used in mobile phone technologies, and the demodulation of these signals, as well as the extra ELF components related to discontinuous transmission at 2 Hz (Challis, 2005). Given that some of the ELF components related to mobile phone handset operation are within the frequency range of human brain activity, it could be speculated that there is some sort of interference to neural activity induced by these low frequency emissions and pulse modulations. Although there is limited research regarding the mechanism of possible interference to neural activity, this hypothesis is supported by recent

research which has suggested that mobile phone-induced changes to the EEG and rCBF are dependent on the pulse modulation of the signal. One research group in particular has argued that pulse modulation of the RF EMF is crucial to induce changes in brain activity and have reported in two separate studies that a pulse-modulated RF EMF, but not a continuous-wave (or base station-like signal), affects the EEG during sleep and waking (Huber et al., 2002), and changes in rCBF (Huber et al., 2005).

Overall, there is limited information regarding the nonthermal mechanisms behind the more consistent mobile phone-induced bioeffects, such as alterations in EEG activity. Although there is some support for an influence of ELF components related to mobile phone handsets on calcium binding, there is currently no definitive evidence for an interaction mechanism explaining the reported relation between mobile phones and biological function. However, the recent results reported by Huber et al., (2002; 2005) do provide some evidence that the ELF pulse modulation component of the signal may be a possible nonthermal mechanism to explain the effects on the EEG and rCBF, which is also supported by the results of a separate study in which changes in the EEG were reported from exposure to a pure ELF signal that did not contain the higher frequencies found in digital mobile phone signals (Cook et al., 2004).

11.7 Possible Methodological Limitations

Due to limitations that existed in previous studies that investigated the effects of RF EMF on human sleep and melatonin, the current study was designed with the aim to overcome these identified limitations. Nevertheless, some possible limitations in relation to the current study and interpretation of the results are acknowledged.

The first limitation is in regards to the statistical procedures utilised and the difficulties that surround multiple comparisons. Although no statistical adjustments were made for the hypothesis-driven analyses regarding the sleep EEG in the first NREM period or for the analysis of melatonin secretion, the significance level for all analyses regarding the time-course of the EEG effect during NREM sleep and all exploratory analyses on the REM sleep EEG were adjusted to account for Type I error (see section 7.4 for details). Given that mobile phone-induced effects tend to be of a small magnitude, particularly in relation to effects on the sleep EEG, this statistical adjustment may have minimised the chance of finding an effect of mobile phone exposure on the analysis of the NREM EEG time-course, or in other frequency ranges outside of the hypothesised regions tested, if an effect existed. Furthermore, no statistical adjustments were made for the analysis of conventional sleep parameters, and therefore interpretations of the mobile phone-induced decrease in REM sleep latency that was found in the current study are limited and requires replication before any conclusions can be drawn.

Another possible limitation of the current study regards the characteristics of the study participants. The sample was comprised of healthy participants aged between 18 an 60 years, and current results are therefore unable to be generalised to younger or older populations, or to people that suffer from health conditions or sleep disorders or disturbances. This may be a particularly important limitation given the recent increase in mobile phone use, particularly among the adolescent population. This limitation is also identified by the WHO, with the most recent WHO research agenda for RF fields (WHO, 2006) identifying human laboratory studies designed to determine possible effects of mobile phone emissions on children and adolescents as the highest priority. They specifically state that “acute effects on cognition and EEGs should be investigated in children exposed to RF fields in the laboratory” and highlight that there are only a few results concerning RF effects on children and adolescents (WHO, 2006).

Additionally, unlike previous studies, the current study investigated both male and female participants. Although the inclusion of both genders in the study population makes the results more generalisable, it may also have led to more variability in the data, particularly in the female participants due to variations in menstrual phase, and therefore the chance of seeing an overall effect of mobile phone exposure on sleep parameters and the sleep EEG may have been reduced.

Particularly pertinent to the effects of mobile phone exposure on melatonin production and onset time, there is a possibility that exposure to sources of bright light in the period immediately prior to coming to the laboratory (as well as the light levels during mobile phone exposure and prior to sleep) could have confounded the results. Light is known to be an important zeitgeber (or time cue) for the biological clock and the circadian system has been shown to be sensitive to exposure to light, particularly when administered during the rising phase of melatonin excretion, which can lead to both a suppression of melatonin and a delay in the melatonin rhythm (for review, see Lack and Wright, 2007). The randomised crossover design of the study would tend to minimise the effects of such extraneous factors, however, the possibility of an influence cannot be completely ruled out, particularly as the participants were still exposed to light during the exposure periods immediately prior to sleep onset which could have potentially led to a phase delay in their melatonin rhythms, thus making it more difficult to see an effect of the RF EMF exposure. This limitation could be overcome in future studies by having the participants arrive at the laboratory earlier, which would allow the researchers to control the levels of light exposure during the period prior to melatonin onset time. It could also be useful to take regular salivary samples both prior to and during exposure, in order to estimate each participants' melatonin onset time and therefore ascertain whether this occurred during the exposure period.

The timing of urine collections and the fact that there were only two samples taken would only have been sufficient to identify a large suppressive effect of RF EMF on melatonin production, and therefore a small or moderate change in melatonin production due to RF EMF exposure would not have been able to be seen using this sampling technique. In addition, the second sample was collected at 06:00 h, which is before the cessation of melatonin excretion and the return of melatonin levels to baseline, and therefore it might also be useful for future studies to collect urine samples at later time-points in order to more accurately assess the whether exposure to mobile phone RF EMF can lead to a suppression or changes in the production and secretion of melatonin.

Additionally, there were limitations in the analyses due to technical problems, and therefore exploratory analysis of the possible effects of mobile phone exposure on parameters of the ECG, such as heart rate variability, were unable to be carried out. Similarly, technical issues also meant that exploratory analyses on the laterality of the mobile phone-induced effects on the NREM sleep EEG, and the possible relationship with sleep spindle activity, were also unable to be performed.

Lastly, it should be noted that the study design utilised in the current research was specifically designed to investigate short-term effects of mobile phone use, and therefore the current results cannot be used as an assessment of possible long-term effects of mobile phone use and exposure.

11.8 Implications of the Current Study

Overall, the results of the current study suggested that a relatively short exposure to the RF EMF emitted by a mobile phone handset is sufficient to induce changes in the sleep EEG during NREM sleep, and may also have an

influence on REM sleep latency and the secretion of the principal melatonin metabolite, aMT6s.

The main implication of the current study is that the results have confirmed the presence of a mobile phone-induced alteration of the NREM sleep EEG. As mentioned previously these results could suggest that subcortical regions, such as the thalamus, may be more sensitive to RF EMF than other structures of the brain, and given the relatively consistent nature of the EEG enhancement being reported in the spindle frequency range by both the current and previous studies, the current results provide important information regarding a possible site of interaction that could be used to further explore the mechanisms behind the mobile phone-induced effects found on both the awake and sleep EEG.

Additionally, the results of the current study lend support to the possibility that individuals could be affected differently by RF EMF exposure and that there may be a subset of the population that are particularly sensitive to such exposures. If this is indeed the case, it may help to explain the slight differences in the enhanced EEG frequencies that have been reported across studies, with the results representing differences in the sample population and therefore a follow-up study of previous participants would seem warranted.

However, perhaps the most important implication of the current results is that, despite consistent mobile phone-induced changes to the sleep EEG and subtle unconfirmed effects on REM sleep latency and melatonin secretion, a persons overall sleep quality, as assessed by the measurement techniques employed in the current study, does not appear to be significantly affected by mobile phone exposure, or by the changes in EEG induced by the mobile phone exposure.

11.9 Recommendations for Future Research

Arguably, the most consistent effects of mobile phone RF EMF emissions have been those reported on human sleep. However, although overall there is support for a mobile phone-induced enhancement of EEG spectral power during NREM sleep, the functional significance and mechanisms of such an effect remain unknown. As mentioned previously, it has been suggested that subcortical regions, namely the thalamus, may be more sensitive to the RF EMF emitted by digital mobile phones, and because spindles are generated in the thalamus, the RF EMF may be stimulating neurons and therefore leading to alterations in spindle frequency activity (Huber et al., 2002). However, to our knowledge, the interaction between mobile phone RF EMF and subcortical structures such as the thalamus has not been investigated, and therefore might be one possible direction for future research regarding the mechanisms behind mobile phone-induced alterations of the sleep EEG.

Similarly, the functional significance of the mobile phone-induced alterations of the EEG during NREM sleep have also not been investigated, and therefore studies exploring the possible significance or consequences of these changes, particularly in relation to health and well-being, would also be warranted. In particular, although research has so far failed to identify mobile phone-related changes in overall sleep quality, there is currently no data on other possible consequences of the mobile phone-induced enhancement in EEG activity, such as possible cognitive or mood changes the following day. Given that one of the reported functions of sleep spindle activity is that of memory consolidation, and that changes in sleep patterns and sleep disorders are related to negative outcomes cognitively (see Walker and Stickgold, 2006 for review), research determining whether the mobile phone-related sleep EEG changes result in adverse cognitive and mood changes would add valuable information regarding the functional significance of the effects found on the sleep EEG.

Another consideration for future research is the inclusion of newer technologies in study protocols. This is particularly important regarding the exposure set-ups or systems used as the majority of studies performed to date have focussed on effects related to 2G mobile phone technology, and with the recent emergence of 3G technology which has a number of different transmission characteristics, possible effects related to 3G mobile phone use, particularly effects that have been found consistently in studies using 2G mobile phones, should be explored. Additionally, future studies should also endeavour to provide clearly defined details of the dosimetry and exposure set-ups used to enable clear and meaningful interpretation of results and to also allow for the possibility of replication.

In regards to study samples, it would be useful for future research to investigate the confirmed or more consistent mobile phone-induced effects that have been found generally among young healthy male participants using more diverse study populations in order to ascertain whether effects also exist or may be heightened in certain population sub-groups, such as children, women, the elderly, or in so called 'hypersensitive' populations. In relation to the results of the current study, investigations on people suffering from various sleep disorders or psychological conditions may add valuable information to our general knowledge regrading mobile phone-induced effects on human sleep. Similarly, the importance of follow-up studies of significant results should also be recognised, and in response to the current results, we have begun replication on a subset of the original sample in order to investigate the possibility of individual differences in response to mobile phone emissions, and also to address some of the possible limitations that were identified in the current study.

More generally, the limitations that have been identified in previous studies should also be addressed, and therefore future research should attempt, where possible, to employ double-blind study conditions, sufficient sample

sizes, relevant exposure parameters, and appropriate statistical tests and corrections, to ensure more powerful and reliable results.

Finally, the results of the current study do not allow for speculations on any long-term effects of mobile phone exposure on human sleep. However, the findings of acute or short-term exposures in the current and previous studies have suggested that the effects of exposure are somewhat transitory, and therefore the possibility of long-term effects is not an obvious corollary of these findings.

11.10 Conclusion

Due to the extensive use of mobile phone technologies in recent years, and the increasing trend of this use, even small influences of RF EMF exposure could have significant outcomes. Although many studies have examined the biological effects of RF EMF on humans, most have concentrated on short-term, whole body or large regional exposures using RF fields much higher than those appropriate to mobile phone emissions.

Arguably, the most consistent effects of mobile phone RF EMF emissions have been those on human sleep. A number of previous studies reported increases in EEG spectral power within the 8 – 13 Hz frequency range during sleep, either following or during RF EMF exposure (Mann and Roschke, 1996; Borbely et al., 1999; Huber et al., 2000; Huber et al., 2002; Huber et al., 2003). Although this mobile phone-induced enhancement has most commonly been seen in the alpha and sleep spindle frequency ranges, the particular frequency at which the effect has been observed has varied slightly between studies, which is most likely attributable to a number of methodological limitations, such as small sample sizes and large variations in exposure parameters. Furthermore, previous results concerning the effects of mobile phone RF EMF on melatonin production and secretion have been

largely inconsistent, with no clear indication of a mobile phone-induced effect on melatonin being reported. However, similar to the studies investigating human sleep, the research on possible effects of mobile phone emissions on human melatonin production have also suffered from a number of limitations, particularly in regards to the exposure parameters and methods of assessing melatonin output that have been used.

Due to the importance of possible health impacts of mobile phone exposure, and given the inconsistencies and limitations of the previous research, the current study aimed to determine the immediate effects of mobile phone RF EMF on human sleep and the secretion of melatonin. The current study also aimed to address and overcome the crucial methodological limitations that were identified in previous research studies in order to produce more meaningful and generalisable results.

The results of the current study have established that a short, 30-minute exposure to the RF EMF emitted by a mobile phone handset can lead to alterations in brain activity during sleep. Specifically, the results showed a significant enhancement in EEG spectral power, which corresponded to the alpha and sleep spindle frequency ranges, following mobile phone exposure. This enhancement was significant in the first NREM sleep period, however, did not appear to be present in subsequent NREM periods or in the EEG during REM sleep, suggesting that the effect is somewhat transitory and does not linger throughout the night, which is consistent with the majority of previous research (Mann and Roschke, 1996; Borbely et al., 1999; Huber et al., 2000; Huber et al., 2003). Additionally, active exposure also led to a significant decrease in REM sleep latency, which was not consistent with previous findings, and therefore requires independent verification before any conclusions can be drawn.

Overall, the total overnight secretion of melatonin, as measured by the amount of urinary metabolite (aMT6s), was unaffected by exposure to the RF

EMF emitted by a mobile phone handset, which was consistent with the majority of previous research. However, there was a significant reduction in aMT6s relative to creatinine concentrations in pre-bedtime samples of a select few participants, which also requires independent verification before a conclusion can be reached regarding these emissions leading to a delay in melatonin onset time, possibly in a sensitive sub-group of individuals.

Given that the current study improved on a number of methodological limitations that existed in previous research, particularly in regards to the provision of adequate dosimetric information and realistic exposure and study conditions, the use of appropriate statistical methods, and the fact that it is the largest study to date to investigate the effects of mobile phone emissions on human sleep, the current results provide strong evidence for a mobile phone-induced effect on human EEG activity during the initial part of sleep. However as mentioned previously, the mechanisms behind this mobile phone-induced effect and the significance of an enhancement of EEG spectral power in the sleep spindle frequency range during the initial part of sleep remains unknown and therefore presents an important step for future research.

In conclusion, the current study has confirmed that a short exposure to the RF EMF emitted by a mobile phone handset immediately prior to sleep is sufficient to induce changes in EEG activity in the initial part of sleep. The consequences or functional significance of this effect are currently unknown and it would be premature to draw conclusions about possible health consequences based on the findings of the current study, however, the current results do suggest that the overall sleep quality is not affected by acute exposure to emissions from a mobile phone handset, regardless of the effects observed on the EEG activity. It should also be emphasised that the current results are only generalisable for acute or short-term exposure to a mobile phone, and therefore speculations regarding the possible effects of

long-term mobile phone exposure cannot be derived from the results of the current study.

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SWINBURNE UNIVERSITY OF TECHNOLOGY

PARTICIPANT INFORMATION AND CONSENT FORM

Joint Swinburne University – Mitcham Private Hospital Project

Participant Information and Consent Form
Version 4 Dated 28 August 2003

Full Project Title: HUMAN PHYSIOLOGICAL RESPONSES TO EXPOSURE TO MOBILEPHONE-TYPE RADIATION

Principal Researcher(s): Associate Professor Andrew Wood, School of BSEE, Swinburne University
Prof Con Stough, School of BSEE, Swinburne University

Associate Researcher(s): Dr Bruce Thompson, Dept Respiratory Medicine, Alfred Hospital

Student Researcher: Sarah Loughran

This Participant Information and Consent Form is 7 pages long. Please make sure you have all the pages.

1. Your Consent

You are invited to take part in the sleep study part of this research project. You may have already participated in the first part of this project, involving the measurement of brain electrical activity, at Swinburne.

This Participant Information contains detailed information about the research project. Its purpose is to explain to you as openly and clearly as possible all the procedures involved in this project before you decide whether or not to take part in it.

Please read this Participant Information carefully. Feel free to ask questions about any information in the document. You may also wish to discuss the project with a relative or friend. Feel free to do this.

Once you understand what the project is about and if you agree to take part in it, you will be asked to sign the Consent Form. By signing the Consent Form, you indicate

that you understand the information and that you give your consent to participate in the research project.

You will be given a copy of the Participant Information and Consent Form to keep as a record.

2. Purpose and Background

The purpose of this project is to investigate whether electromagnetic energy (EME) from digital mobile phones affects human performance.

A total of 60 people will participate in the sleep study part of this project.

Previous experience in an overseas study has shown that sleep patterns are altered during the first hour or so of sleep after exposure to EME from a simulated mobile phone. There is also concern that output of a particular hormone, melatonin, may also be affected.

You are invited to participate in this research project because of the wide use of mobile phones and associated technologies. While there is no substantive evidence that health is affected, any suggestion of altered human performance deserves careful study.

The results of this research may be used to help a researcher (Honours or PhD student) to obtain a degree.

3. Procedures

Participation in this project will involve measuring the quality of your sleep during an overnight stay in the laboratory after mobile phone use. In addition, the output of the hormone melatonin, which acts as a marker for the biological clock, will be estimated.

You will be asked to participate in two sessions approximately one week apart from about 9.30 pm in the evening. For recording purposes you will be asked to wear an array of electrodes that sit gently on the scalp to record the natural activity produced by the brain. A small quantity of water-soluble gel is used to ensure a good contact between electrode and the skin. The electrodes are used to record activity and cannot give you a shock.

A standard digital mobile phone will rest in a cradle placed next to the cheek. The phone will be in the normal position against the face during each session. For up to 1 hour of one session you will be exposed to the normal EME emission that any user of mobile phones experiences during the course of a call. Normally, a phone will only transmit on full power in weak reception areas, but in this study it will transmit at full power all the time. In one of the two sessions the mobile phone will not transmit anything at all, that is, you will not be exposed to any EME, neither you nor the investigator will be aware of whether you are being exposed to EME or not.

If you agree to be included in this study, you will, at the conclusion of the testing described above, retire to bed in a private room in the laboratory at about 10.30 pm where you will be able to sleep as normal until around 6 am the next morning. You

will be required to wear the electrode headset (which does permit comfortable sleep) to record brain activity during the night. In addition, muscle activity will be recorded by applying a pair of electrodes to the chin and eye movement by placing small electrodes next to the eyelids. A sterilised nasal thermistor will be inserted to record respiration. If you find the latter to be uncomfortable you will be asked to wear a belt around the chest to do the same thing. These electrodes will be attached to a recording device which will monitor brain, muscle and breathing activity and eye movements throughout the night. If you need to go to the toilet, you can be unplugged from the recorder during this time.

You will also be asked to collect urine, in order that the output of the hormone melatonin can be assessed. You will be asked to go to the toilet at 8 pm then collect all urine produced after that at the hospital, in separate marked bottles for 'pre bedtime' and 'post bedtime'.

In order to become accustomed to sleeping in the laboratory environment, you will be asked to sleep overnight starting the day before the first mobile phone exposure session. There is no need to stay in the laboratory after getting up and you can attend to your normal daily duties before returning to the laboratory between 9.00 pm and 9.30 pm that evening.

You will not be aware of whether the exposure is sham or real. If you receive a sham exposure in your first session you will receive a real mobile phone EME exposure during the second, and vice versa.

4. Possible Benefits

Possible benefits include ensuring that mobile phone technology, which has already shown itself to be immensely beneficial for society, has no untoward side-effects.

5. Possible Risks

The EMF emissions involved are below the limits set by Australian Standard 2772 (currently in use by the Australian Communications Authority) which covers emissions from communications equipment including mobile phones and which manufacturers abide by. Any biological effects that have been reported to occur below these levels have not been proven to be of any threat to human health. In addition, the present debate over possible health effects associated with EMF is concerned mainly with long-term exposure to these fields rather than the immediate responses, some of which this study aims to identify. Some people report tingling sensations or headache associated with mobile phone use. Previous double-blind studies have been unable to link exposure with symptoms, but you are, of course, free to withdraw at any time.

6. Alternatives to Participation

Participation in this study is entirely voluntary.

7. Privacy, Confidentiality and Disclosure of Information

Any information obtained in connection with this project and that can identify you will remain confidential. It will only be disclosed with your permission, except as required by law. Data recorded during sleep monitoring and for melatonin assay will be given a code to prevent a third party from linking data with your name. During the study, the data will be kept in the possession of the investigator when needed as reference, but otherwise kept locked in a secure filing cabinet in the office of the Senior Investigator, A/Prof Andrew Wood. If you give us your permission by signing the Consent Form, we plan to publish the results of group data in a research journal.

In any publication, information will be provided in such a way that you cannot be identified.

8. New Information Arising During the Project

During the research project, new information about the risks and benefits of the project may become known to the researchers. If this occurs, you will be told about this new information. This new information may mean that you can no longer participate in this research. If this occurs, the person(s) supervising the research will stop your participation.

9. Results of Project

We can provide you with a reprint of our research findings if you would like one.

10. Further Information or Any Problems

If you require further information or if you have any problems concerning this project (for example, any side effects), you can contact the principal researcher or the associate researcher. The researchers responsible for this project are:

A/Prof Andrew Wood: 9214 8867 or 0403 077 977 (AH)

Dr Bruce Thompson: 9276 3476

Furthermore, if you feel that you have suffered any adverse effects or symptoms resulting from your exposure to the electromagnetic field emitted by the mobile phone, you can report this information to the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) at the following website:

http://www.arpansa.gov.au/pubs/nir/repform.doc

11. Other Issues

If you have any complaints about any aspect of the project, the way it is being conducted or any questions about your rights as a research participant, then you may contact

Name: The Chair
Human Experimentation Ethics Committee
Swinburne University of Technology
PO Box 218
HAWTHORN, VIC 3122

Telephone: 9214 5225

You will need to tell this person the name of one of the researchers given in section 10 above.

12. Participation is Voluntary

Participation in any research project is voluntary. If you do not wish to take part you are not obliged to. If you decide to take part and later change your mind, you are free to withdraw from the project at any stage.

Your decision whether to take part or not to take part, or to take part and then withdraw, will not affect your relationship with Swinburne University.

Before you make your decision, a member of the research team will be available to answer any questions you have about the research project. You can ask for any information you want. Sign the Consent Form only after you have had a chance to ask your questions and have received satisfactory answers.

If you decide to withdraw from this project, please notify a member of the research team before you withdraw. This notice will allow that person or the research supervisor to inform you if there are any special requirements linked to withdrawing.

13. Ethical Guidelines

This project will be carried out according to the *National Statement on Ethical Conduct in Research Involving Humans* (June 1999) produced by the National Health and Medical Research Council of Australia. This statement has been developed to protect the interests of people who agree to participate in human research studies.

The ethical aspects of this research project have been approved by the Human Research Ethics Committee of Swinburne University and the Alfred Hospital.

14. Reimbursement for your costs

You will not be paid for your participation in this project.

However, you will be reimbursed $50 per night for the inconvenience and travel costs that you incur as a result of participating in this trial.

Date: 28th August 2003

Signed:

(Chief Investigator)

School of Biophysical Sciences & Electrical Engineering
Swinburne University of Technology
John St
Hawthorn Vic 3122

SWINBURNE UNIVERSITY OF TECHNOLOGY

Joint Swinburne University – Mitcham Private Hospital Project

Consent Form
Version 4 Dated 28/8/03
Mitcham Private Hospital Site

Full Project Title: HUMAN PHYSIOLOGICAL RESPONSES TO EXPOSURE TO MOBILEPHONE-TYPE RADIATION

I …… have read, or have had read to me in my first language, and I understand the Participant Information version 4 dated 28 August 2003.

I freely agree to participate in this project according to the conditions in the Participant Information, realising that I can withdraw at any time.

I will be given a copy of the Participant Information and Consent Form to keep.

The researcher has agreed not to reveal my identity and personal details if information about this project is published or presented in any public form.

To my knowledge, I do not suffer from epilepsy.

To my knowledge, I do not suffer from sleep apnoea or severe asthma

To my knowledge, I do not carry Hepatitis B or AIDS viruses

Participant's Name (printed) ……

Signature Date

Name of Witness to Participant's Signature (printed) ……

Signature Date

Researcher's Name (printed) ……

Signature Date

Note: All parties signing the Consent Form must date their own signature.

Please indicate if you consent to being contacted about participation in further related research by placing a tick in the appropriate box.

☐ Yes ☐ No

Fill out days 1-7 below	COMPLETE IN MORNING						
	I went to bed last night at:	I got out of bed this morning at:	Last night I fell asleep in:	I woke up during the night: (Record number of times)	When I woke up for the day, I felt: (Check one)	Last night I slept for a total of: (Record number of hours)	My sleep was disturbed by: (List any mental, emotional, physical, or environmental factors that affected your sleep, e.g. stress, snoring, physical discomfort, temperature)
DAY 1 day _____ date_____	_____ PM/AM	_____ AM/PM	_____ Minutes	_____ Times	Refreshed Somewhat Refreshed Fatigued	_____ Hours	_____ _____ _____
DAY 2 day _____ date _____	_____ PM/AM	_____ AM/PM	_____ Minutes	_____ Times	Refreshed Somewhat Refreshed Fatigued	_____ Hours	_____ _____ _____
DAY 3 day _____ date _____	_____ PM/AM	_____ AM/PM	_____ Minutes	_____ Times	Refreshed Somewhat Refreshed Fatigued	_____ Hours	_____ _____ _____
DAY 4 day _____ date _____	_____ PM/AM	_____ AM/PM	_____ Minutes	_____ Times	Refreshed Somewhat Refreshed Fatigued	_____ Hours	_____ _____ _____
DAY 5 day _____ date _____	_____ PM/AM	_____ AM/PM	_____ Minutes	_____ Times	Refreshed Somewhat Refreshed Fatigued	_____ Hours	_____ _____ _____
DAY 6 day _____ date _____	_____ PM/AM	_____ AM/PM	_____ Minutes	_____ Times	Refreshed Somewhat Refreshed Fatigued	_____ Hours	_____ _____ _____
DAY 7 day _____ date _____	_____ PM/AM	_____ AM/PM	_____ Minutes	_____ Times	Refreshed Somewhat Refreshed Fatigued	_____ Hours	_____ _____ _____

STUDY:.....

Subject:
Date:

NEO FFI Personality Inventory

Shade circles ●
Do not ⊗ ∅ ✓

Instructions

This section contains 48 statements. Read each statement carefully. For each Statement fill in the circle that best represents your opinion. Please make sure that your answer is in the correct circle.

Fill in **1** if you strongly disagree or the statement is definitely false.

Fill in **2** if you disagree or the statement is mostly false.

Fill in **3** if you are neutral on the statement, you cannot decide, or the statement is about equally true or false.

Fill in **4** if you agree or the statement is mostly true.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
	1	2	3	4	5
1. I am not a worrier.	1	2	3	4	5
2. I like to have a lot of people around me.	1	2	3	4	5
3. I don't like to waste my time daydreaming.	1	2	3	4	5
4. I try to be courteous to everyone I meet	1	2	3	4	5
5.I keep my belongings clean and neat	1	2	3	4	5
6. I often feel inferior to others	1	2	3	4	5
7. I laugh easily.	1	2	3	4	5
8. Once I find the right way to do something, I stick to it.	1	2	3	4	5
9. I often get into arguments with my family and co-workers	1	2	3	4	5
10. I'm pretty good about pacing myself so as to get things done on time	1	2	3	4	5
11. When I'm under a great deal of stress, sometimes I feel like I'm going to pieces	1	2	3	4	5
12. I don't consider myself especially "lighthearted".	1	2	3	4	5
13. I am intrigued by the patterns I find in art and nature	1	2	3	4	5
14. Some people think I'm selfish and egotistical	1	2	3	4	5
15. I am not a very methodical person	1	2	3	4	5
16. I rarely feel lonely or blue	1	2	3	4	5
17. I really enjoy talking to people	1	2	3	4	5
18. I believe letting students hear controversial speakers can only confuse and mislead them	1	2	3	4	5
19. I would rather cooperate with others than compete with them	1	2	3	4	5
20. I try to perform all the tasks assigned to me conscientiously	1	2	3	4	5
21. I often feel tense and jittery	1	2	3	4	5
22. I like to be where the action is	1	2	3	4	5
23. Poetry has little or no effect on me	1	2	3	4	5
24. I tend to be cynical and skeptical of other's intentions	1	2	3	4	5
25. I have a clear set of goals and work toward them in an orderly fashion	1	2	3	4	5
26. Sometimes I feel completely worthless	1	2	3	4	5
27. I usually prefer to do things alone	1	2	3	4	5

NEO FFI Personality Inventory continued...

Fill in **1** if you strongly disagree or the statement is definitely false.

Fill in **2** if you disagree or the statement is mostly false.

Fill in **3** if you are neutral on the statement, you cannot decide, or the statement is about equally true or false.

Fill in **4** if you agree or the statement is mostly true.

Fill in 5 if you strongly agree or the statement is definitely true.

Shade circles ●
Do not ⊗ ∅ ⊘

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
28. I often try new and foreign foods	1	2	3	4	5
29. I believe that most people will take advantage of you if you let them	1	2	3	4	5
30. I waste a lot of time before settling down to work	1	2	3	4	5
31. I rarely feel fearful or anxious	1	2	3	4	5
32. I often feel as if I am bursting with energy	1	2	3	4	5
33. I seldom notice the moods or feelings that different environments produce	1	2	3	4	5
34. Most people I know like me	1	2	3	4	5
35. I work hard to accomplish my goals	1	2	3	4	5
36. I often get angry at the way people treat me	1	2	3	4	5
37. I am a cheerful, high-spirited person	1	2	3	4	5
38. I believe we should look to our religious authorities for decisions on moral issues	1	2	3	4	5
39. Some people think of me as cold and calculating	1	2	3	4	5
40. When I make a commitment, I can always be counted on to follow through	1	2	3	4	5
41. Too often, when things go wrong, I get discouraged and feel like giving up.	1	2	3	4	5
42. I am not a cheerful optimist	1	2	3	4	5
43. Sometimes when I am reading poetry or looking at a work of art, I feel a chill or wave of excitement	1	2	3	4	5
44. I'm hard-headed and tough-minded in my attitudes	1	2	3	4	5
45. Sometimes I'm not as dependable or reliable as I should be	1	2	3	4	5
46. I am seldom sad or depressed	1	2	3	4	5
47. My life is fast-paced	1	2	3	4	5
48. I have little interest in speculating on the nature of the universe or the human condition	1	2	3	4	5
49. I generally try to be thoughtful and considerate	1	2	3	4	5
50. I am a productive person who always gets the job done	1	2	3	4	5
51. I often feel helpless and want someone else to solve my problems	1	2	3	4	5
52. I am a very active person	1	2	3	4	5
53. I have a lot of intellectual curiosity	1	2	3	4	5
54. If I don't like people, I let them know it	1	2	3	4	5
55. I never seem to be able to get organized	1	2	3	4	5
56. At times I have been so ashamed I just wanted to hide	1	2	3	4	5
57. I would rather go my own way than be a leader of others	1	2	3	4	5
58. I often enjoy playing with theories or abstract ideas.	1	2	3	4	5
59. I necessary, I am willing to manipulate people	1	2	3	4	5
60. I strive for excellence in everything I do	1	2	3	4	5

50879

THE PROFILE OF MOOD STATES

Subject ID ☐☐☐ Study Code ☐☐☐ Test Session ⓪①②③④

Below is a list of words that describe feelings people have. Please read each one carefully. Then fill in ONE circle under the answer to the right which best describes **HOW YOU HAVE BEEN FEELING DURING THE PAST WEEK INCLUDING TODAY**.

Shade Circles Like This--> ●
Not Like This--> ⊗ ✓

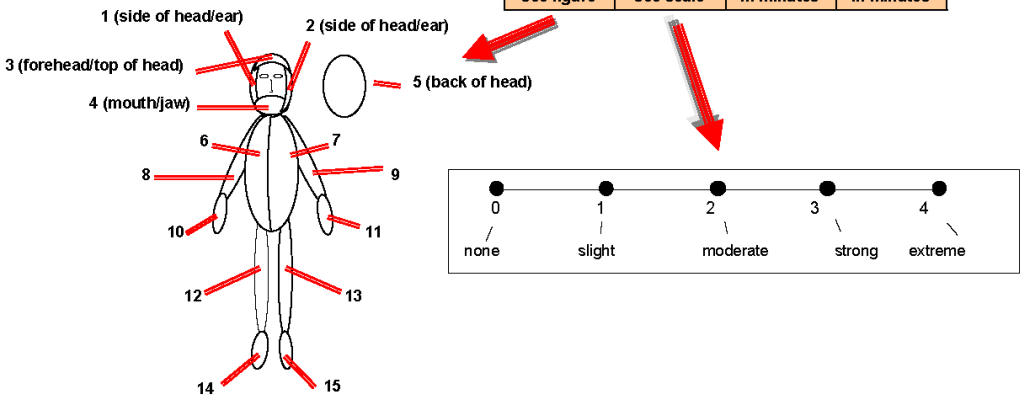
	NOT AT ALL	A LITTLE	MODERATELY	QUITE A BIT	EXTREMELY
1. Friendly	⓪	①	②	③	④
2. Tense	⓪	①	②	③	④
3. Angry	⓪	①	②	③	④
4. Worn out	⓪	①	②	③	④
5. Unhappy	⓪	①	②	③	④
6. Clear-headed	⓪	①	②	③	④
7. Lively	⓪	①	②	③	④
8. Confused	⓪	①	②	③	④
9. Sorry for things done	⓪	①	②	③	④
10. Shaky	⓪	①	②	③	④
11. Listless	⓪	①	②	③	④
12. Peeved	⓪	①	②	③	④
13. Considerate	⓪	①	②	③	④
14. Sad	⓪	①	②	③	④
15. Active	⓪	①	②	③	④
16. On edge	⓪	①	②	③	④
17. Grouchy	⓪	①	②	③	④
18. Blue	⓪	①	②	③	④
19. Energetic	⓪	①	②	③	④
20. Panicky	⓪	①	②	③	④
21. Hopeless	⓪	①	②	③	④
22. Relaxed	⓪	①	②	③	④
23. Unworthy	⓪	①	②	③	④
24. Spiteful	⓪	①	②	③	④
25. Sympathetic	⓪	①	②	③	④
26. Uneasy	⓪	①	②	③	④
27. Restless	⓪	①	②	③	④
28. Unable to concentrate	⓪	①	②	③	④
29. Fatigued	⓪	①	②	③	④
30. Helpful	⓪	①	②	③	④
31. Annoyed	⓪	①	②	③	④
32. Discouraged	⓪	①	②	③	④
33. Resentful	⓪	①	②	③	④

	NOT AT ALL	A LITTLE	MODERATELY	QUITE A BIT	EXTREMELY
34. Nervous	⓪	①	②	③	④
35. Lonely	⓪	①	②	③	④
36. Miserable	⓪	①	②	③	④
37. Muddled	⓪	①	②	③	④
38. Cheerful	⓪	①	②	③	④
39. Bitter	⓪	①	②	③	④
40. Exhausted	⓪	①	②	③	④
41. Anxious	⓪	①	②	③	④
42. Ready to fight	⓪	①	②	③	④
43. Good natured	⓪	①	②	③	④
44. Gloomy	⓪	①	②	③	④
45. Desperate	⓪	①	②	③	④
46. Sluggish	⓪	①	②	③	④
47. Rebellious	⓪	①	②	③	④
48. Helpless	⓪	①	②	③	④
49. Weary	⓪	①	②	③	④
50. Bewildered	⓪	①	②	③	④
51. Alert	⓪	①	②	③	④
52. Deceived	⓪	①	②	③	④
53. Furious	⓪	①	②	③	④
54. Efficient	⓪	①	②	③	④
55. Trusting	⓪	①	②	③	④
56. Full of pep	⓪	①	②	③	④
57. Bad-tempered	⓪	①	②	③	④
58. Worthless	⓪	①	②	③	④
59. Forgetful	⓪	①	②	③	④
60. Carefree	⓪	①	②	③	④
61. Terrified	⓪	①	②	③	④
62. Guilty	⓪	①	②	③	④
63. Vigorous	⓪	①	②	③	④
64. Uncertain about things	⓪	①	②	③	④
65. Bushed	⓪	①	②	③	④

MOBILE OR CELLULAR PHONE

Have you ever used a mobile phone?		*'Y' or 'N'*
Over the last week or so, how much would you say that you use the mobile phone per day?		*in minutes*
Over the last year or so, how much would you say that you use the mobile phone per day?		*in minutes*
How many years have you used the mobile phone for?		*in years*

DOES THE MOBILE PHONE CAUSE...			If 'Y' which area?	If 'Y' how strong?	If 'Y' onset	If 'Y' offset
Non-painful sensations of tingling?		*'Y' or 'N'*				
Non-painful sensations of pressure?		*'Y' or 'N'*				
Non-painful sensations of heat?		*'Y' or 'N'*				
Non-painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
Painful sensations of tingling?		*'Y' or 'N'*				
Painful sensations of pressure?		*'Y' or 'N'*				
Painful sensations of heat?		*'Y' or 'N'*				
Painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
			see figure	*see scale*	*in minutes*	*in minutes*



Please indicate the effect of the mobile phone's EMF on the following things (check box with 'x')

PSYCHOLOGICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Anxiety					
Clear headedness					
Drowsiness					
Positive mood					
General psychological wellbeing not included above					

PHYSICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Heart rate					
Blood pressure					
Breathing rate					
Breathing difficulties					
Physical fatigue					
General physical wellbeing not included above					

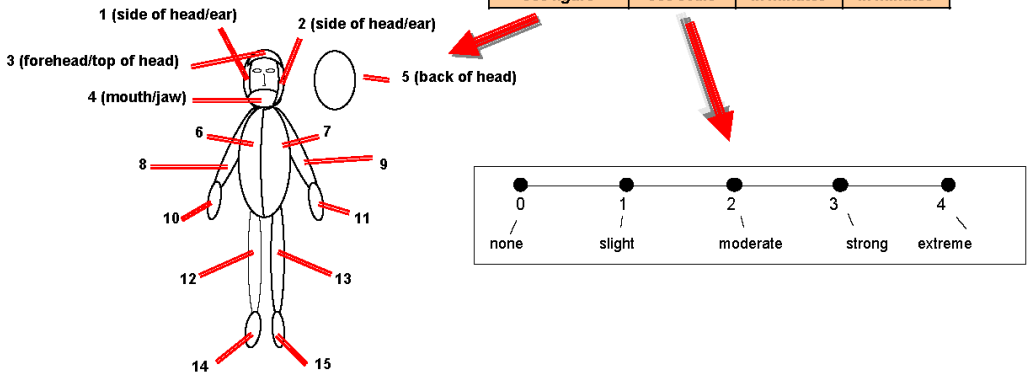
If there were any other effects that the mobile phone has on you that were not addressed earlier, please describe below...

If there is anything else that you would like to add, please do so below...

HANDS FREE MOBILE PHONE

Have you ever used a hands free phone?		*'Y' or 'N'*
Where do you have the phone when you use the hands free attachment?		*describe*
How far from your body is the phone when you use the hands free attachment?		*in metres*
Over the last week or so, how much would you say that you use the hands free phone per day?		*in minutes*
Over the last year or so, how much would you say that you use the hands free phone per day?		*in minutes*
How many years have you used the hands free phone for?		*in years*

DOES THE HANDS FREE PHONE CAUSE...			If 'Y' which area?	If 'Y' how strong?	If 'Y' onset	If 'Y' offset
Non-painful sensations of tingling?		*'Y' or 'N'*				
Non-painful sensations of pressure?		*'Y' or 'N'*				
Non-painful sensations of heat?		*'Y' or 'N'*				
Non-painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
Painful sensations of tingling?		*'Y' or 'N'*				
Painful sensations of pressure?		*'Y' or 'N'*				
Painful sensations of heat?		*'Y' or 'N'*				
Painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
			see figure	*see scale*	*in minutes*	*in minutes*



Please indicate the effect of the hands free phone's EMF on the following things (check box with 'x')

PSYCHOLOGICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Anxiety					
Clear headedness					
Drowsiness					
Positive mood					
General psychological wellbeing not included above					

PHYSICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Heart rate					
Blood pressure					
Breathing rate					
Breathing difficulties					
Physical fatigue					
General physical wellbeing not included above					

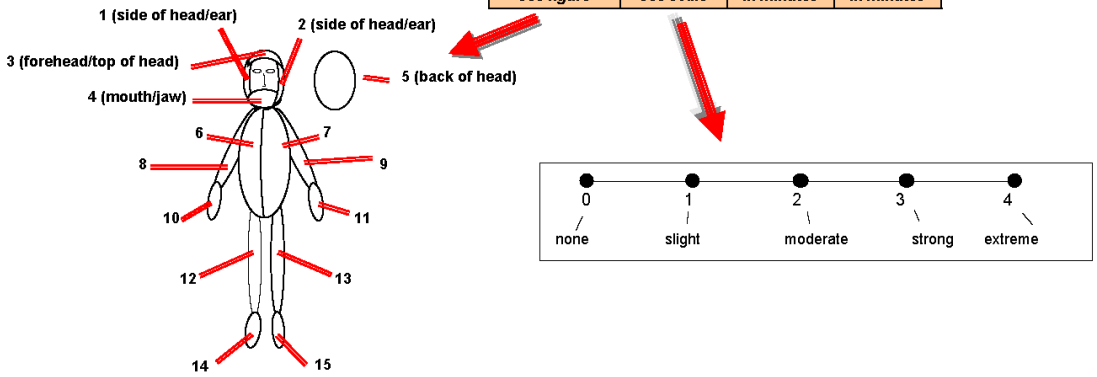
If there were any other effects that the hands free phone has on you that were not addressed earlier, please describe below...

If there is anything else that you would like to add, please do so below...

SEWING MACHINE

Have you ever used a sewing machine?		*'Y' or 'N'*
Over the last week or so, how much would you say that you use the sewing machine per day?		*in minutes*
Over the last year or so, how much would you say that you use the sewing machine per day?		*in minutes*
How many years have you used the sewing machine for?		*in years*

DOES THE SEWING MACHINE CAUSE…			If 'Y' which area?	If 'Y' how strong?	If 'Y' onset	If 'Y' offset
Non-painful sensations of tingling?		*'Y' or 'N'*				
Non-painful sensations of pressure?		*'Y' or 'N'*				
Non-painful sensations of heat?		*'Y' or 'N'*				
Non-painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
Painful sensations of tingling?		*'Y' or 'N'*				
Painful sensations of pressure?		*'Y' or 'N'*				
Painful sensations of heat?		*'Y' or 'N'*				
Painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
			see figure	*see scale*	*in minutes*	*in minutes*



Please indicate the effect of the sewing machine's EMF on the following things (check box with 'x')

PSYCHOLOGICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Anxiety					
Clear headedness					
Drowsiness					
Positive mood					
General psychological wellbeing not included above					

PHYSICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Heart rate					
Blood pressure					
Breathing rate					
Breathing difficulties					
Physical fatigue					
General physical wellbeing not included above					

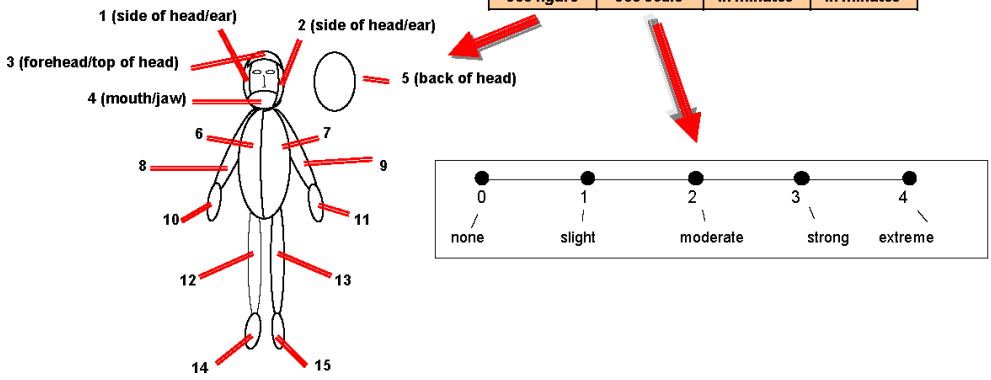
If there were any other effects that the sewing machine has on you that were not addressed earlier, please describe below…

If there is anything else that you would like to add, please do so below…

RADIO (car, home stereo etc.)

Have you ever used a radio?		*'Y' or 'N'*
How far from your body is the radio when you usually use it?		*in metres*
Over the last week or so, how much would you say that you use the radio per day?		*in minutes*
Over the last year or so, how much would you say that you use the radio per day?		*in minutes*
How many years have you used the radio for?		*in years*

DOES THE RADIO CAUSE…			If 'Y' which area?	If 'Y' how strong?	If 'Y' onset	If 'Y' offset
Non-painful sensations of tingling?		*'Y' or 'N'*				
Non-painful sensations of pressure?		*'Y' or 'N'*				
Non-painful sensations of heat?		*'Y' or 'N'*				
Non-painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
Painful sensations of tingling?		*'Y' or 'N'*				
Painful sensations of pressure?		*'Y' or 'N'*				
Painful sensations of heat?		*'Y' or 'N'*				
Painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
			see figure	*see scale*	*in minutes*	*in minutes*



Please indicate the effect of the radio's EMF on the following things (check box with 'x')

PSYCHOLOGICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Anxiety					
Clear headedness					
Drowsiness					
Positive mood					
General psychological wellbeing not included above					

PHYSICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Heart rate					
Blood pressure					
Breathing rate					
Breathing difficulties					
Physical fatigue					
General physical wellbeing not included above					

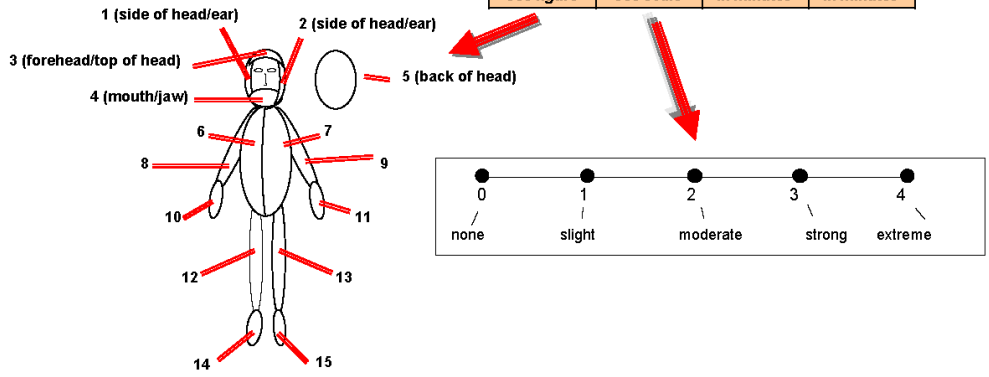
If there were any other effects that the radio has on you that were not addressed earlier, please describe below…

If there is anything else that you would like to add, please do so below…

WALKMAN (OR DISKMAN)

Have you ever used a walkman?		*'Y' or 'N'*
How far from your body is the walkman when you use it?		*in metres*
Over the last week or so, how much would you say that you use the walkman per day?		*in minutes*
Over the last year or so, how much would you say that you use the walkman per day?		*in minutes*
How many years have you used the walkman for?		*in years*

DOES THE WALKMAN CAUSE...			If 'Y' which area?	If 'Y' how strong?	If 'Y' onset	If 'Y' offset
Non-painful sensations of tingling?		*'Y' or 'N'*				
Non-painful sensations of pressure?		*'Y' or 'N'*				
Non-painful sensations of heat?		*'Y' or 'N'*				
Non-painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
Painful sensations of tingling?		*'Y' or 'N'*				
Painful sensations of pressure?		*'Y' or 'N'*				
Painful sensations of heat?		*'Y' or 'N'*				
Painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
			see figure	*see scale*	*in minutes*	*in minutes*



Please indicate the effect of the walkman's EMF on the following things (check box with 'x')

PSYCHOLOGICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Anxiety					
Clear headedness					
Drowsiness					
Positive mood					
General psychological wellbeing not included above					

PHYSICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Heart rate					
Blood pressure					
Breathing rate					
Breathing difficulties					
Physical fatigue					
General physical wellbeing not included above					

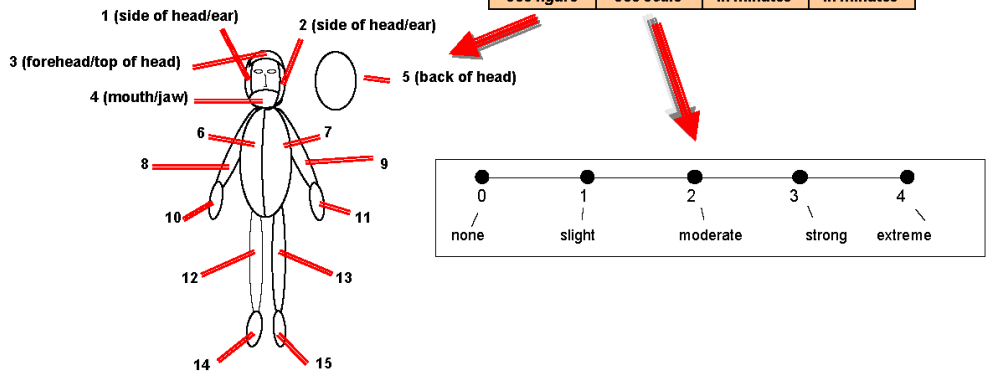
If there were any other effects that the walkman has on you that were not addressed earlier, please describe below...

If there is anything else that you would like to add, please do so below...

HAIR DRYER

Have you ever used a hair dryer?		*'Y' or 'N'*
Over the last week or so, how much would you say that you use the hair dryer per day?		*in minutes*
Over the last year or so, how much would you say that you use the hair dryer per day?		*in minutes*
How many years have you used the hair dryer for?		*in years*

DOES THE HAIR DRYER CAUSE…			If 'Y' which area?	If 'Y' how strong?	If 'Y' onset	If 'Y' offset
Non-painful sensations of tingling?		*'Y' or 'N'*				
Non-painful sensations of pressure?		*'Y' or 'N'*				
Non-painful sensations of heat?		*'Y' or 'N'*				
Non-painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
Painful sensations of tingling?		*'Y' or 'N'*				
Painful sensations of pressure?		*'Y' or 'N'*				
Painful sensations of heat?		*'Y' or 'N'*				
Painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
			see figure	*see scale*	*in minutes*	*in minutes*



Please indicate the effect of the hair dryer's EMF on the following things (check box with 'x')

PSYCHOLOGICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Anxiety					
Clear headedness					
Drowsiness					
Positive mood					
General psychological wellbeing not included above					

PHYSICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Heart rate					
Blood pressure					
Breathing rate					
Breathing difficulties					
Physical fatigue					
General physical wellbeing not included above					

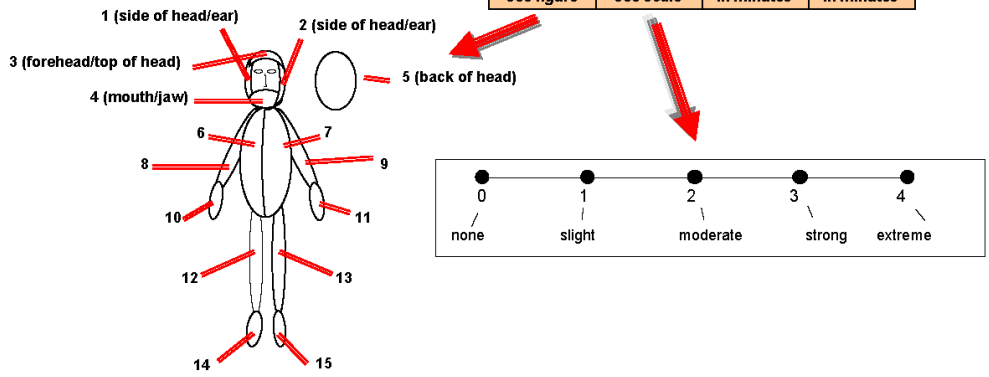
If there were any other effects that the hair dryer has on you that were not addressed earlier, please describe below…

If there is anything else that you would like to add, please do so below…

COMPUTER

Have you ever used a computer?		*'Y' or 'N'*
Over the last week or so, how much would you say that you use the computer per day?		*in minutes*
Over the last year or so, how much would you say that you use the computer per day?		*in minutes*
How many years have you used the computer for?		*in years*

DOES THE COMPUTER CAUSE...			If 'Y' which area?	If 'Y' how strong?	If 'Y' onset	If 'Y' offset
Non-painful sensations of tingling?		*'Y' or 'N'*				
Non-painful sensations of pressure?		*'Y' or 'N'*				
Non-painful sensations of heat?		*'Y' or 'N'*				
Non-painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
Painful sensations of tingling?		*'Y' or 'N'*				
Painful sensations of pressure?		*'Y' or 'N'*				
Painful sensations of heat?		*'Y' or 'N'*				
Painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
			see figure	*see scale*	*in minutes*	*in minutes*



Please indicate the effect of the computer's EMF on the following things (check box with 'x')

PSYCHOLOGICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Anxiety					
Clear headedness					
Drowsiness					
Positive mood					
General psychological wellbeing not included above					

PHYSICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Heart rate					
Blood pressure					
Breathing rate					
Breathing difficulties					
Physical fatigue					
General physical wellbeing not included above					

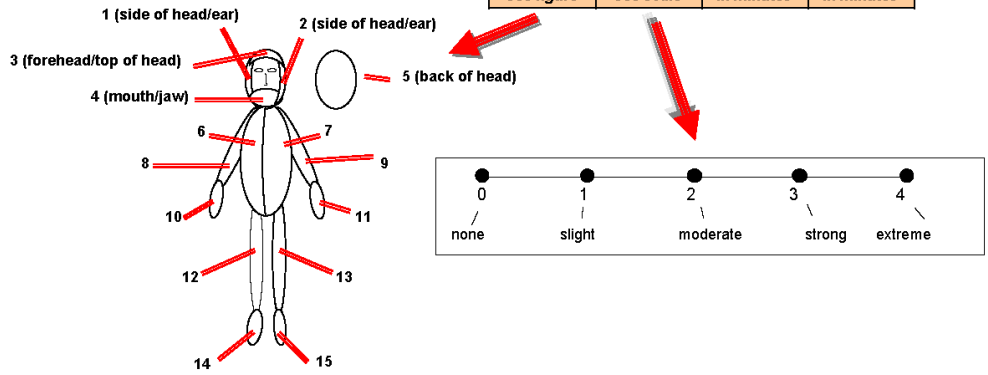
If there were any other effects that the computer has on you that were not addressed earlier, please describe below...

If there is anything else that you would like to add, please do so below...

TELEVISION

Have you ever used a television?		*'Y' or 'N'*
How far from your body is the television when you use it?		*in metres*
Over the last week or so, how much would you say that you use the television per day?		*in minutes*
Over the last year or so, how much would you say that you use the television per day?		*in minutes*
How many years have you used the television for?		*in years*

DOES THE TELEVISION CAUSE...			If 'Y' which area?	If 'Y' how strong?	If 'Y' onset	If 'Y' offset
Non-painful sensations of tingling?		*'Y' or 'N'*				
Non-painful sensations of pressure?		*'Y' or 'N'*				
Non-painful sensations of heat?		*'Y' or 'N'*				
Non-painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
Painful sensations of tingling?		*'Y' or 'N'*				
Painful sensations of pressure?		*'Y' or 'N'*				
Painful sensations of heat?		*'Y' or 'N'*				
Painful skin irritations (e.g. redness, itching)?		*'Y' or 'N'*				
			see figure	*see scale*	*in minutes*	*in minutes*



Please indicate the effect of the television's EMF on the following things (check box with 'x')

PSYCHOLOGICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Anxiety					
Clear headedness					
Drowsiness					
Positive mood					
General psychological wellbeing not included above					

PHYSICAL	strong decrease	slight decrease	no change	slight increase	strong increase
Heart rate					
Blood pressure					
Breathing rate					
Breathing difficulties					
Physical fatigue					
General physical wellbeing not included above					

If there were any other effects that the television has on you that were not addressed earlier, please describe below...

If there is anything else that you would like to add, please do so below...

Subject No.
Date:
Time:

Demographic Information Sheet

Please provide the following information:
(If you do not want to answer a question please leave it blank.)

1. Age: years _____ months _____

2. Gender (circle): Female Male

3. Females: How many days ago did your menstrual cycle end? _____

4. Handedness (circle): Left Right Both

5. Have you ever suffered an epileptic seizure? Yes / No
   If yes, please specify: _____

6. Have you ever suffered any serious head injuries or periods of unconsciousness? Yes / No
   If yes, please specify: _____

7. Do you have any hearing problems? Yes / No
   If yes, please specify: _____

8. Are you currently taking any form of medication? Yes / No
   If yes, please specify: _____

9. Is English your first language? Yes / No

Please fill out the following information about your use of the following substances.
Note: If the questions are not applicable to you please write N/A.

10. Have you ever smoked tobacco? Yes / No

10.1 When was the last time you smoked tobacco? *Please specify*

Hours ☐ *(If today)* *Days* ☐ *(If within last week)* *More than one week ago* ☐ *More than a month ago* ☐ *Other* ☐

10.2 How often do/did you smoke tobacco? *Please specify approximately how many cigarettes per day/week and the strength (e.g. <4mg, 4mg, 8mg, 12mg, 16mg) of tobacco smoked.*

These Days (past year)	**Amount**	**Strength**
Daily		
Weekly		
Less than Weekly		
Monthly		
Other		

When you Smoked MOST	**Amount**	**Strength**
Daily		
Weekly		
Less than Weekly		
Monthly		
Other		

10.3 How long have you or did you smoke tobacco for? _____

11. Have you ever consumed alcohol? Yes / No

11.1 When was the last time you consumed alcohol? *Please specify*

Hours ☐ *(if today)* *Days* ☐ *(if within last week)* *More than one week ago* ☐ *More than a month ago* ☐ *Other* ☐

11.2 How often do you consume alcohol? *Please specify approximately how many times per day/week etc.*

Daily ☐ *Weekly* ☐ *Less than Weekly* ☐ *Monthly* ☐ *Other* ☐

11.3 How many standard drinks do you consume in a session? _____

11.4 How many standard drinks do you consume in a week? _____

11.5 How often during the last year have you needed a drink in the morning to get yourself going after a heavy drinking session? *Please Specify*

Never ☐ *Less than monthly* ☐ *Monthly* ☐ *Weekly* ☐ *Daily or almost daily* ☐

11.6 How long have you been drinking alcohol for? _____

11.7 How often do/did you drink alcohol? *Please specify approximately how many standard drinks per day/week etc.*

These Days (past 2 years)	
Daily	
Weekly	
Less than Weekly	
Monthly	
Other	

When you Drank MOST	
Daily	
Weekly	
Less than Weekly	
Monthly	
Other	

12. Have you ever consumed caffeine (e.g. tea, coffee, coke)? Yes / No

12.1 When was the last time you consumed caffeine? *Please specify*

Hours ☐ *(If today)* *Days* ☐ *(If within last week)* *More than one week ago* ☐ *More than a month ago* ☐ *Other* ☐

12.2 How often do you or did you consume caffeine? *Please specify approximately how many cups*

These Days (past year)	
Daily	
Weekly	
Less than Weekly	
Monthly	
Other	

12.3 How long have you/did you drink caffeine for? _____

13.1 Have you ever used any illicit drugs (e.g. Cannabis, ecstasy, cocaine, amphetamines, heroin, inhalants)

Yes / No

If yes, please specify_____

13.2 When was the last time you used illicit drugs? *Please specify*

Hours		*Days*		*More than one week ago*		*More than a month ago*		*Other*	
(if today)		*(Of within last week)*							

13.3 How often do/did you use illicit drugs for? *Please specify approximate quantities per day/week etc.*

	These Days (past 2 years)		**When you Used the MOST**	
	How often	***Quantity***	***How often***	***Quantity***
Daily				
Weekly				
Less than Weekly				
Monthly				
Other				

SLEEP NEUROREPORT

The effect of electromagnetic fields emitted by mobile phones on human sleep

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Previous research has suggested that exposure to radiofrequency electromagnetic fields increases electroencephalogram spectral power in non-rapid eye movement sleep. Other sleep parameters have also been affected following exposure. We examined whether aspects of sleep architecture show sensitivity to electromagnetic fields emitted by digital mobile phone handsets. Fifty participants were exposed to electromagnetic fields for 30 min prior to sleep. Results showed a decrease in rapid eye movement sleep latency and increased electroencephalogram spectral power in the 11.5–12.25 Hz frequency range during the initial part of sleep following exposure. These results are evidence that mobile phone exposure prior to sleep may promote rapid eye movement sleep and modify the sleep electroencephalogram in the first non-rapid eye movement sleep period. *NeuroReport* 16:1973–1976 © 2005 Lippincott Williams & Wilkins.

Keywords: cellular phones, electromagnetic fields, Global System for Mobile Communication, mobile phones, non-REM sleep, radiofrequency bioeffects, radiofrequency, REM latency, sleep, spectral analysis

Introduction

The development of mobile phone technology has led to substantial advancements in communication; however, this expansion and increase in use has also led to concerns about possible effects this technology may have on human health and performance. Of particular interest are the effects digital mobile phone emissions may have on conventional sleep parameters and the sleep electroencephalogram (EEG). Mobile phones transmit and receive signals using electromagnetic fields (EMFs) in the radiofrequency band. The Global System for Mobile Communications (GSM) is currently the most widely used digital mobile phone service, operating at the 900 or 1800 MHz frequency bands [1]. Owing to this, a considerable amount of research into sleep variables and other biological effects has centred on exposures from GSM mobile phones that operate around 900 MHz. Present international standards permit GSM 900 mobile phones to transmit at a pulsed power of 2 W with an average output of 0.25 W [1].

A number of studies have reported an increase in EEG spectral power within the 8–13 Hz frequency range, in both awake [2–4] and sleep states following radiofrequency EMF exposure [5–9]. Enhancements reported during sleep, however, have not been entirely consistent, with some earlier studies failing to find an effect [10–12], and others finding that the effects differ in terms of particular frequency band [5–9]. These reported inconsistencies following mobile phone exposures are likely to be due to a number of methodological issues, such as small sample sizes, variations in power output, exposure duration, and distances from the source of exposure. Differences in duration of sleep episodes measured may also contribute, with substantial variation in these ranging from short daytime sleep episodes with sleep-deprived volunteers, to full overnight sleep episodes. It is thus not surprising that there are differences in study outcomes, and it is noteworthy that there have been several reports of enhanced sleep spectral power in the 8–15 Hz frequency range following radiofrequency EMF exposure [5–9]. Of these results, one study reported an increase in non-rapid eye movement (non-REM) sleep EEG power in the 11.5–12.25 and 13.5–14 Hz frequency ranges, which was present in the initial 30 min after lights out and only after 15 min of radiofrequency EMF exposure [7]. The same group also examined exposure prior to sleep using a more ecologically valid testing regime and also found an enhancement in the α-band, but this time in the 12.25–13.5 Hz frequency range [8]. Thus, although there are complexities in the literature, there is support for an enhancement in EEG spectral power during non-REM sleep, with the variability in the frequency ranges suggesting that the particular frequency subcomponent may be sensitive to differences in methodology.

In addition to changes in spectral power, other conventional sleep parameters, such as sleep latency, rapid eye movement (REM) sleep, and waking after sleep onset, have also been reported to be affected by radiofrequency EMF exposure [5,9–11]. Unlike spectral power changes, however, there is no consistency in the conventional sleep parameter findings. Further, that the positive findings [5,9] have been tested with stronger methodological control (including dosimetry) with negative outcomes, suggests that there are no effects of radiofrequency EMF on conventional sleep parameters [6,8,10–12].

The aim of the current study was thus to test for effects of mobile phone radiofrequency EMF on human sleep patterns. In order to improve on previous research limitations and simulate real-life exposure conditions and sleep habits, the present study exposed participants to pulsed high-frequency EMF emitted by an actual mobile phone handset, with continuous transmission and constant power output, for a period of 30 min prior to a full night-time sleep episode. To this end, we attempted to replicate the work of Huber *et al.* [7,8] and test the hypotheses that the 11.5–12.25, 12.25–13.5, and 13.5–14 Hz frequency bands would be enhanced following radiofrequency EMF exposure. Additionally, we tested the hypothesis that radiofrequency EMF exposure influences conventional sleep parameters, although as described above, no effects were predicted.

Materials and methods

Participants

Fifty-five healthy volunteers (30 male and 25 female participants), aged between 18 and 60 years (mean=30.6 years, SD=13.4 years), participated in the study. Participants were instructed to maintain a regular sleep–wake schedule on the days prior to each study night and were required to abstain from caffeine and alcohol consumption once they had arrived at the laboratory. They were also restricted from using personal mobile phones or communication devices on all of the adaptation and experimental nights. Participants suffering from epilepsy or any sleep disorder were excluded from the study. This reduced the sample to 50 (27 male and 23 female participants; mean age=27.9 years, SD=10.9 years) as five participants who were found to have sleep disorders were excluded from the analyses. The Human Research Ethics Committee of Swinburne University and The Alfred Hospital approved the study protocols, and all volunteers gave written, informed consent prior to participation.

Experimental design

Participants slept a total of four nights (22:30–06:00 h) in a sleep laboratory, attending two experimental sessions 1 week apart. Each of the two experimental nights was preceded by an adaptation night designed to help participants acclimatize to the laboratory conditions and also to rule out the presence of any sleep disorders. The experimental night consisted of a randomized EMF exposure schedule using a double-blind crossover design.

During sleep, electroencephalogram (EEG, C4-A1/C3-A2), electrocardiogram, electrooculogram, submental electromyogram, SaO_2 and nasal airflow were monitored along with thoracic and abdominal respiration, and leg movements, using the Compumedics S-series polysomnography system (Compumedics Ltd, Abbotsford, Victoria, Australia). Sleep signals were sampled at 125 or 250 Hz, depending on specific equipment used. EEG signals were high-pass filtered at 0.3 Hz and low-pass filtered at 30 Hz. Respiratory and leg signals were used as an exclusion measure and will not be included in any analyses. All EEG electrode impedances were below 5 kΩ at the start of each recording.

Participants were exposed to either 'active' or 'sham' exposure condition for 30 min prior to a full night-time sleep episode. In order to minimize the possibility of interference with the EMF signal from the mobile phone, electrodes were attached following exposure, leaving approximately 20 min between the end of exposure and lights off.

Electromagnetic field exposure

On both experimental nights, participants sat comfortably in chairs with a mobile phone cradle placed on the head and a standard GSM digital phone mounted on the right side of the head. The phone was positioned so that the speaker was located over the auditory canal and the antenna situated over the right temporal region, with the microphone aligned towards the corner of the mouth to simulate normal use.

The GSM digital mobile phone used was a modified Nokia 6110 (Nokia Group, Helsinki, Finland) that was set to continuously transmit at a peak power of 2 W, with a mean power output of 0.25 W, using a link to a laptop computer and software provided by the manufacturer. The signal emitted by the antenna was an 894.6 MHz radiofrequency field pulsed with a frequency of 217 Hz and a duty cycle of 12.5%, resulting in a pulse width of 576 μs (26th frame not idle). The specific absorption rate, which refers to the rate at which the human head absorbs energy from the mobile phone handset, was measured by EMC Technologies (Melbourne, Australia). The specific absorption rate of the exposed hemisphere averaged over 10 g was 0.11 W/kg, with a peak value of 0.29 W/kg.

The audio circuits of the phone were disconnected and padding was placed between the handset and its cover to ensure that both the researcher and participants were not given acoustic cues revealing the operational status of the phone. The padding also served to eliminate any heat being felt by the participant that may have been generated from extended battery operation. Additionally, a white noise signal was used in the background in order to mask any residual sound from the handset's operation. Participants were asked at the conclusion of the experiment whether they had been able to detect when the phone was transmitting.

Data analysis

Sleep stages were visually scored for 30-s epochs, according to standard criteria [13], by an experienced sleep technician who was blinded to the experimental conditions. Using Neuroscan Edit (Compumedics Ltd) and Matlab software (Natick, Massachusetts, USA), C3 and C4 EEG data were first averaged together and analysed to provide power spectral density estimates for each consecutive epoch (fast Fourier transform routine, Hanning window, averages over 4-s epochs) for the first 30 min of each participant's initial non-REM sleep period. Sleep onset was defined as the first occurrence of stage 2 sleep [5–8]. Artefact removal was performed by visual inspection and only artefact-free epochs were used for further analysis. Statistical analyses were performed using SPSS statistical package version 11.5

(SPSS Inc., Chicago, Illinois, USA). Significance levels were kept at 0.05 for all analyses: for the three frequency bands this was because they were hypothesis driven, and for the conventional sleep parameters analyses this was because they were treated as exploratory only.

Results

A repeated-measures analysis of variance revealed a decrease in REM sleep latency following pulse-modulated EMF exposure [F(1,48)=5.797, P=0.02]. Other parameters, such as percentage of stage 3 and 4 sleep, arousal index, sleep efficiency, REM sleep percentage, non-REM sleep percentage and total sleep time showed no evidence of alteration (Table 1).

Spectral analysis of the sleep EEG from the first 30 min of the first non-REM period revealed a significant enhancement of EEG power density in the 11.5–12.25 Hz frequency range following EMF exposure [F(1,48)=5.56, P=0.022] (Fig. 1). No significant enhancement was present in the 12.25–13.5 or the 13.5–14 Hz frequency ranges. Effect sizes (partial η^2) were also calculated for the 0–25 Hz region and are shown in Fig. 2. The largest effect is seen at 11.5 Hz, partial η^2=0.105, which corresponds to a relatively modest effect of the EMF on EEG spectral power in the first non-REM period. A comparison between individuals showed that the enhancement of EEG spectral power was not significantly affected by age or sex; however, there was more variance in the female participants, presumably due to menstrual phase variation.

An exploratory analysis was also performed to explore the temporal evolution of the increase in spectral power. The results showed that the enhancement of spectral power in the 11.5–12.25 Hz frequency range was not present until 10 min into the first non-REM period (first 10 min, P=0.396; second 10 min, P=0.024; third 10 min, P=0.081).

As condition order was not perfectly balanced (24 had sham followed by exposure, 26 had exposure followed by sham), this factor was included in all of the analyses and was not found to significantly relate to the experimental condition. Additionally, participants were asked at the conclusion of the experiment whether they had been able to detect when the phone was transmitting. Only 27 out of 50 participants correctly classified the status of the phone (binomial distribution, P=0.672), and this number was still not significant when those that could not even make a choice were removed (27 out of 44 correct responses, P=0.174).

Table 1 Effects of EMF exposure on visually scored sleep variables

	Sham	Active	P-values
Total sleep time (min)	323.1 (46.86)	324.4 (44.42)	0.844
Sleep onset latency (min)	37.37 (39.42)	36.97 (32.5)	0.956
REM latency (min)	107.77 (56.43)	90.17 (42.57)	0.020
Arousal index (per hour)	9.76 (4.16)	10.41 (3.2)	0.162
Sleep efficiency (%)	88.18 (7.85)	88.56 (8.65)	0.739
Stage 1 (min)	10.75 (5.79)	11.65 (5.16)	0.195
Stage 2 (min)	150.82 (41.37)	148.17 (41.56)	0.613
Slow-wave sleep	101.86 (29.4)	102.31 (28.36)	0.895
Non-REM (%)	81.74 (6.23)	81.74 (5.87)	0.988
REM sleep (min)	59.63 (21.5)	59.79 (21.39)	0.949

All night mean values (standard deviation in parentheses for n=50). Sleep variables based on visual scoring for the two experimental conditions, sham or active exposure. Sleep latency: interval from lights out until the onset of stage 2 sleep. Sleep efficiency: total sleep time as a percentage of total time in bed. Arousal index: number of wakings per hour. REM latency: interval between sleep onset and the onset of the first REM period. Non-REM sleep: percentage of total sleep time. A two-way repeated-measures analysis of variance (between factor 'order', within factor 'condition' and interaction 'condition × order') revealed a decrease in REM sleep latency, P=0.020. EMF, electromagnetic field; REM, rapid eye movement; non-REM, non-rapid eye movement.

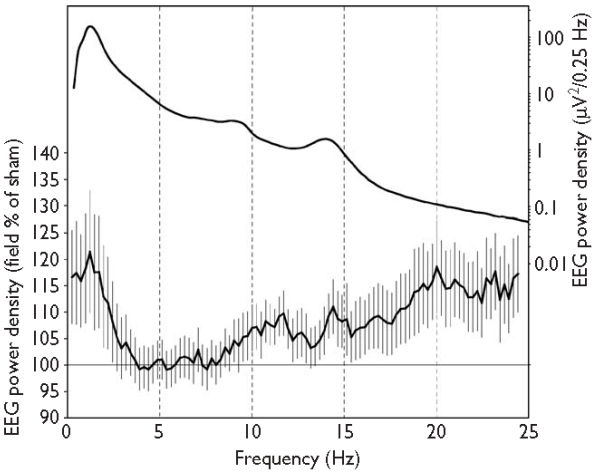

Fig. 1 Mean electroencephalogram (EEG) power density spectrum of the first 30 min of the first non-rapid eye movement sleep episode (n=50 participants). The upper curve is the average spectrum of the sham exposure night for the central derivations (C3 and C4, referenced to linked mastoids). The lower curve represents the average electromagnetic field exposure spectrum expressed as a percentage of the corresponding value from the sham condition (mean ± SEM for 0.25 Hz bins, n=50). A two-way repeated-measures analysis of variance for the factors condition (sham vs. active) and sequence, and their interaction (condition × sequence) was computed, revealing a significant enhancement of power in the 11.5–12.25 Hz range. No significant sequence or interaction effects were present.

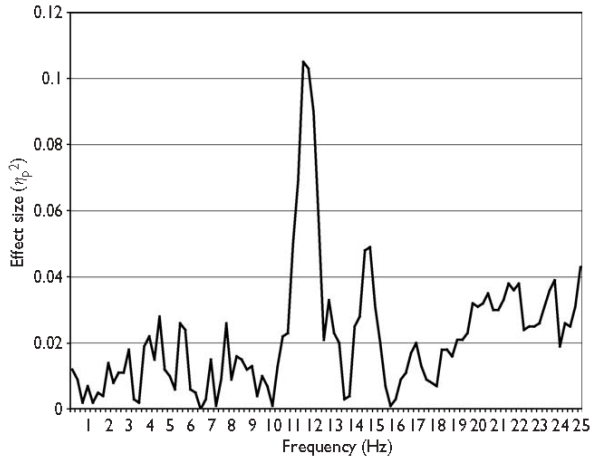

Fig. 2 Effect sizes of electromagnetic field exposure on the first 30 min of the first non-rapid eye movement period. Effect sizes for each 0.25 Hz bin (0–25 Hz) are illustrated and were calculated using the formula $\eta_p^2 = SS_{effect}/(SS_{effect} + SS_{error})$.

Discussion

We have shown that 30 min exposure to GSM digital mobile phone EMF prior to sleep affects the subsequent sleep EEG. The increase in EEG spectral power was present in the first 30 min of non-REM sleep and was enhanced in the frequency range corresponding to slow sleep spindles. Enhancement of non-REM sleep spectral power induced by high-frequency EMF in the frequency ranges largely determined by slow and fast sleep spindles has also been found in a number of previous studies [5–8], and although the frequencies at which power was enhanced have been somewhat inconsistent, we have shown that mobile phone radiofrequency does induce changes in the 11.5–12.25 Hz frequency range in the first non-REM period. Interestingly, the effect was not present until 10 min into the first non-REM period, which is similar to previous research that has shown that the enhancement of spectral power following EMF exposure increased as the night progressed. The significance of an enhancement of spectral power in this frequency range during the initial part of sleep remains unknown, and although the enhancement was found in the frequencies corresponding to slow sleep spindles, any changes in the number of sleep spindles present or their amplitude or duration cannot be identified by the current analysis. It has been suggested previously that subcortical regions, such as the thalamus, may be more sensitive to radiofrequency EMF than other structures of the brain, and because spindle oscillations are generated in the thalamus [14], radiofrequency EMF may be stimulating cortical neurons to induce alterations in sleep spindle activity [7].

The exploratory results also suggest that exposure to radiofrequency EMF prior to sleep decreases REM sleep latency. Unlike previous research that has reported an overall suppressive effect of EMF exposure on REM sleep [9–11], the current study found no differences in the percentage of REM sleep between the active and sham exposure conditions, and is the first study to find that exposure to radiofrequency EMF prior to sleep decreases REM latency. No influence of EMF exposure on any of the other sleep variables analysed was found, which is consistent with previous research that has also failed to identify any difference in conventional sleep parameters [5–8,12].

The significance of such a decrease in REM latency is difficult to determine, although a reduction in REM sleep onset has often been seen in unmedicated depressed patients and also other psychopathological conditions [15,16]. Other common sleep disturbances observed in depression, such as reduction in slow wave sleep, prolongation of the first REM period and increases in REM density, however, were not seen in the current study following EMF exposure. One possible mechanism behind the observed decrease in REM latency could involve innervation of cholinergic neurons, as there is considerable evidence that cholinergic activity plays an important role in the regulation of behavioural state, particularly in the initiation and maintenance of REM sleep [17–19]. As a decrease in REM sleep latency following EMF exposure has not been reported previously however, this effect needs to be replicated before any conclusions can be drawn.

Conclusion

Exposure to EMF emitted by digital mobile phones prior to sleep significantly affects sleep EEG by enhancing power in the 11.5–12.25 Hz frequency range. The exploratory analyses also suggested that radiofrequency EMF may cause a decrease in REM latency. This study thus demonstrates that a short exposure to mobile phone-type radiation has an effect on subsequent sleep EEG, although no conclusions can be made regarding adverse health consequences as the mechanisms of the effects are still unknown.

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Does evening exposure to mobile phone radiation affect subsequent melatonin production?

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Abstract

Purpose: To test whether exposure to the emissions from a digital mobile phone handset prior to sleep alters the secretion of melatonin.

Materials and methods: In a double-blind cross-over design, 55 adult volunteers were both actively exposed or sham-exposed (in random order on successive Sunday nights) to mobile phone emissions for 30 min (0.25 W average power). Urine collection occurred immediately prior to retiring to bed and on rising the next morning. Melatonin output was estimated from principal metabolite concentrations (6-sulphatoxymelatonin (aMT6s) via radioimmunoassay), urine volumes and creatinine concentrations.

Results: Total melatonin metabolite output (concentration × urine volume) was unchanged between the two exposure conditions (active 14.1 ± 1.1 μg; sham 14.6 ± 1.3 μg). The pre- and post-bedtime outputs considered separately were also not significantly different, although the pre-bedtime value was less for active versus sham exposure. When melatonin metabolite output was estimated from the ratio of aMT6s to creatinine concentrations, the pre-bedtime value was significantly less ($p = 0.037$) for active compared to sham. Examination of individual responses is suggestive of a small group of 'responders'.

Conclusions: Total nighttime melatonin output is unchanged by mobile phone handset emissions, but there could be an effect on melatonin onset time.

Keywords: *Melatonin, mobile phone, cell phone, radiofrequency, sulphatoxymelatonin, aMT6s*

Introduction

In view of the extensive worldwide use of mobile telephony, in particular the increasing use by younger people, it is imperative that possible adverse effects on human health are investigated fully. Because of the reported suppression of pineal melatonin in rodents in response to rapidly reversed geomagnetic fields (Lerchl et al. 1991), any forms of rapidly changing environmental magnetic fields have come under suspicion as potentially being able to alter melatonin secretion. Experiments carried out at 50/60 Hz power frequencies on several mammal species including humans have yielded conflicting results (Henshaw & Reiter 2005), but previous studies from our laboratory have indicated a possible time delay in plasma melatonin evening rise following exposure to 50 Hz circularly-polarized magnetic fields (Wood et al. 1998). Henshaw & Reiter (2005), in reviewing the literature, found support for the hypothesis of melatonin disruption in those studies of human populations chronically exposed to both electric and magnetic fields. They have also argued that melatonin disruption could be due to other factors than field level, such as transients or switching, or to field type (electric rather than magnetic). Although the radiofrequency (RF) radiation from mobile (cellular) phone handsets is quite different in character from 50/60 Hz fields (the main tissue effect at RF due to heating rather than induced currents), the 217 Hz modulations and magnetic fields associated with the pulsed battery power supply offer the possibility of an extremely low frequency (ELF) effect.

To date, studies on human volunteers have not revealed any consistent changes in patterns of melatonin release in regard to mobile phone use: Three reporting no significant changes (de Seze et al. 1999, Mann et al. 1998, Radon et al. 2001) and two reporting significant reductions (Burch et al. 2002, Jarupat et al. 2003). In these studies there has been a

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large disparity in exposure durations and the number of times individuals were exposed (ranging from a single exposure of a few hours to exposures of several weeks) and in the method of assessing melatonin output (from samples of serum melatonin, salivary melatonin or urinary melatonin metabolite). These experimental details are compared in Table I.

Other hormones, such as growth hormone, cortisol, luteinizing hormone, thyrotropin, adrenocorticotropin, prolactin and follicle stimulating hormone have also been studied, without any significant alterations being noted (de Seze et al. 1998, Mann et al. 1998). In a series of experiments on several rodent species, Vollrath and co-workers were unable to show any consistent effects of mobile phone-type radiation on either serum melatonin nor the rate limiting enzyme N-Acetyltransferase (Vollrath et al. 1997). On the other hand, another group has reported evidence for melatonin reversal of changes attributed to mobile phone radiation-induced free-radical activity (Ayata et al. 2004, Koyu et al. 2005, Oktem et al. 2005, Ozguner et al. 2004). Thus, if they have occurred at all, the previous electric and/or magnetic field (EMF)-related changes in melatonin levels have been reductions or suppressions.

Because of the disruption in sleep patterns caused by collecting blood samples during an overnight study, melatonin output is more conveniently estimated by measuring concentrations of the principal metabolite 6-sulphatoxymelatonin (aMT6s) in urine. The 2-h values have been shown to correlate well ($r = 0.72$) with plasma melatonin collected at the same time (Nowak et al. 1987) and morning urine concentrations with peak plasma melatonin concentrations ($r = 0.76$) (Markey et al. 1985).

The purpose of this study was to investigate whether the immediate effect of mobile phone use on overnight melatonin secretion causes a reduction in urinary melatonin metabolite in a group of 55 adult volunteers staying overnight in a sleep laboratory. It forms part of a larger study on the possible effects of mobile phone radiation on sleep parameters (Loughran et al. 2005).

Methods

Subjects

Sixty subjects were recruited to the study, but five of these withdrew for personal reasons after provision for their participation had been made. The final study sample thus comprised 55 healthy volunteers aged from 18–60 years (Mean = 30.6, SD = 13.4 years). Subjects were recruited from advertisements in local and state newspapers, and posters located at several universities and organizations in Melbourne. Those reporting a history of epilepsy or sleep disorders were excluded. In the final sample there were 30 males and 25 females, 49 of whom were right handed. No participant reported any psychological or neurological condition, serious head injury or extended periods of unconsciousness.

The study took place at a purpose-made laboratory (Eastern Sleep Disorders Service, Mitcham Private Hospital, Victoria, Australia), which consisted of three individual bedrooms, a central monitoring room, together with other facilities. Participants provided written consent and the study was approved by the relevant university and hospital human experimentation ethics committees.

Exposure apparatus

A modified commercially available digital mobile phone (Nokia 6110) transmitting in 'test mode' was used for the exposure period in all testing sessions. For the purposes of exposure hazard evaluation, it was assumed that the radiated power would be the maximum permissible, although it is unlikely for this to occur in practice because of the use of adaptive power control. Typical everyday exposures (except for brief intervals) are one or two orders of magnitude less than this maximum value. Therefore, software provided by the manufacturer was used to set the phone to transmit at 0.25 W average power with the standard Global System for Mobile (GSM) 895 MHz RF signal including 217 Hz pulse modulation (1/8 duty cycle). There was no phase modulation nor 26th pulse blanking present in the signal. Commands were sent from a laptop computer to the phone via a data cable, which was disconnected once the output was set ('test mode'). The power output was checked by an independent person using a test antenna connected to a power meter before handing over the handsets to the experimenter, who was thus blind to the status of the phone. Phone outputs were also checked by an independent laboratory (the Australian Radiation Protection and Nuclear Safety Agency) three times during the project. In addition, Specific Absorption Rate (SAR) measurements were conducted (EMC Technologies, Tullamarine, Victoria) inside a Specific Anthropmorphic Mannequin (SAM) phantom using a precision robot RF Dosimetric Assessment System (DASY4). The average SAR value measured over 10 g of tissue was 0.674 W/kg and the peak SAR value measured in-line with the phone's antenna over the area corresponding to the temporal lobe was 0.110 W/kg.

A non-metallic welding helmet was modified to create a headset that the mobile phone could be attached to; the visor was removed and a plastic arm was constructed so the phone rested against the subject's right cheek. The active or sham exposure

Table I. Comparison of human studies of mobile phone radiation and melatonin output. Outcomes commented on in case of statistically significant changes reported.

Author	Group Size	Exposure details	Exposure duration	Number of repeats	Measure	Outcome	Comment
Laboratory studies							
Mann et al. 1998	24 M	Antenna 0.2 W/m^2 GSM-type	8 hr (23:00 – 07:00)	1 × Exposed; 1 × Sham	Serum melatonin, 60 min intervals	NS	Subsequent nights, random order
de Seze et al. 1999	19 M	i) GSM and ii) 1.8 GHz DCS handset	2 h/day (late afternoon)	Exposed 5 d/wk for 4 wk	Serum melatonin, 60 min intervals	NS	Trends pre- during- and post- 4 wk exposure period studied
Radon et al. 2001	8 M	Antenna 1 W/m^2 (estimated SAR 25 mW/kg) GSM-type	4 h/day (50% day, 50% night)	20 × Exposed; 5 × Sham	Salivary melatonin; 30 min intervals	NS	Other hormones measured
Jarupat et al. 2003	8 F	1.9 GHz mobile phone handset†	6 × 30 min per h (19:00 – 01:00)	1 × Exposed; 1 × Sham	Salivary melatonin, at 19:00 & 02:00	36% reduction for sample taken at 02:00	
Population-based studies							
Burch et al. 2002 (Study 1)	149 M	Self-assessment of 'cell phone'‡ use	> 25 min/day compared to no use		Urinary melatonin metabolite	NS	Performed 1997
Burch et al. 2002 (Study 2)	77 M	As above	As above		As above	34% reduction, for overnight data	Performed 1998, larger % of > 25 min/day category

†Details of how the RF power output was maintained not given; ‡Mixture of analog and digital use.
NS, not significant.

was for 30 min duration immediately prior to retiring to bed, and also prior to the attachment of recording electrodes and other sensors.

Although the handset's loudspeaker circuit had been disabled, a just-perceptible 'buzz' could be heard from other components in the handset when transmitting. This was only noticeable in quiet environments and with the handset out of its pouch and pressed to the ear. During testing, wads of plastic foam were placed in the pouch to absorb this noise. Since the laboratory was an extremely quiet environment (purpose-built for sleep studies), the elimination of aural cues from the buzzing of circuitry was even more acute. During the 30-min active/sham exposure period, a white noise signal was provided to mask any residual sound from the handset. This was created by turning on the TV receiver in the bedroom and tuning this to an unused channel. On completion of the second active/sham exposure, subjects were asked to state whether they thought the phone had been on or off on that particular occasion. Of the 50 who responded, 27 were correct in their judgement, 17 incorrect and 6 were unsure. The probability of a correct guess in a random choice was 0.5 (25 responses). The level of significance for 27/50 not being due to chance was not significant ($p > 0.15$). Even if the unsure responses were removed (27 correct out of 44) the correct responses do not achieve statistical significance ($\chi^2 = 2.273$, $p = 0.132$).

Design

A double-blind crossover design was used to collect the data. Participants attended the laboratory on Saturday and Sunday nights on two consecutive weekends. The Saturday nights were familiarization nights, to enable participants to become accustomed to sleeping in a strange environment and with monitoring sensors (relating to the sleep component of the study) attached. Participants arrived just after 21:30 h on each of the four nights. They were instructed not to use mobile phones or pass urine after 20:00 h on these nights. On arrival, they were required to complete forms giving demographics information, details of any medications used and a personality/mood assessment scale. An electric and magnetic fields (EMF) exposure questionnaire was given to assess possible electromagnetic hypersensitivity. A sleep log was also maintained for the 7 days leading up to each experimental night. The study was carried out over a 13-month period (July 2003 – August 2004), avoiding weekends when daylight saving time commenced or finished. The median values for mobile phone daily use and years of duration were reported to be 8 min per day and 4 years respectively.

The 30-min active/sham-exposure period occurred on one of the two Sunday nights, during the time (approx. 1 h) prior to getting into bed, with the opposite condition occurring the following Sunday. During this time the participants were instructed to sit and look at a white screen. Immediately after the 30 min of active/sham phone exposure, subjects were required to visit the bathroom to perform a urine collection. This involved measuring the urine volume, taking a 10 ml sample then discarding the remainder. Sensors were then attached for the sleep monitoring component, a task which normally occupied 15 – 20 min, before subjects got into bed. The lights were turned off after the experimenter had checked that monitoring data were being recorded successfully. This was normally completed just after 23:00 h. During the night, an infrared camera allowed the experimenter to check for abnormal movement. Subjects were roused at 06:00 h the next morning. A total of 28 subjects received a sham exposure and the remaining 27 an active exposure on the first weekend.

During the night and on first rising in the morning, voided urine was collected to give a total volume output from the time of going to bed to rising. Again, this volume was recorded, a 10 ml sample was taken and the remainder discarded.

Measures

The concentration of the melatonin metabolite 6-sulphatoxymelatonin (aMT6s, also known as 6-OHMS) was estimated in duplicate in the urine samples via ^{125}I radio-immunoassay. This used an assay kit from Stockgrand Ltd (Guildford, UK) with the assay itself carried out by ProSearch International, PO Box 515, Malvern, Victoria, Australia. In order to provide a standardized measure of aMT6s, determination of urine creatinine (Cr) was also carried out (ARL Pathology, St Kilda Road, Melbourne, Australia) in the samples collected. Although not part of the data reported here, sleep variables were recorded using a polysomnography system.

Statistics

Since each subject acted as their own control, statistical significance was assessed using the paired *t*-test.

Results

There were no significant differences in pre-bedtime or post-bedtime urine volumes either between exposure conditions or between sequences of collection (volume in ml $\pm$ SE, Pre-bedtime: 234 $\pm$ 17 sham;

246 ± 22 exposed: Post-bedtime: 344 ± 21 sham; 373 ± 25 exposed). The amounts of aMT6s in the urine (sample concentration × volume collected) are shown in Table II. The total aMT6s output (±SE) for the two conditions are: exposed 14.1 ± 1.1 μg; sham 14.6 ± 1.3 μg. Neither these values nor the separate pre- and post-bedtime values are significantly different from each other (paired comparisons).

Because of possible errors in estimation of total volume of urine output, it has been suggested that, since the amount of creatinine output is constant over a given period, the urinary concentration of this substance should be inversely proportional to urine volume produced in that period (Klante et al. 1997). The ratio of aMT6s to creatinine concentrations should therefore be equivalent to aMT6s amount. These are shown in the final two columns of Table II. Particularly in regard to the pre-bedtime data, the coefficients of variation are reduced by approximately one-third and the reduction in aMT6s (referenced to creatinine concentration) is significant ($p = 0.037$, one-tailed comparison). Separate analyses of the two exposure orders yield similar reductions, but fail to reach significance (Mean ± SE; order sham then active: 7.7 ± 1.7 reduced to 5.6 ± 0.8; active then sham: 7.9 ± 2.2 to 5.7 ± 1.0 ng aMT6s/mg Creatinine). Note that the post-bedtime data for aMT6s concentration is slightly raised for the exposed case (which could be interpreted as a phase delay), but the corresponding normalized values are essentially unchanged.

If the exposure to RF were to cause a delay rather than a suppression of melatonin secretion (effect on onset time) the ratio of pre- to post-bedtime aMT6s would be expected to be less for active rather than sham exposure. Neither the ratios, nor their log-transformed values differ significantly (Sham ratio ± SE: 0.46 ± 0.3; exposed ratio 0.43 ± 0.3; $p = 0.20$, one-tailed paired comparison) although the change was in the hypothesized direction. In order to check that this reduction was not a consequence of subjects collecting the first urine sample earlier (by chance) on the exposure night, the times at which sleep data recording commenced (which was recorded automatically) was checked. The average times were 23:20:56 on the sham night and 23:26:35 on the active night (SE = ±2 min 40 s and 3 min 40 s respectively). Thus, if anything, the 1st urine collection was later on the RF exposure night.

A more detailed breakdown of individual changes in pre-bedtime normalized aMT6s is shown in Figure 1. Clearly, there are four individuals whose changes represent substantial reductions, the

Table II. Amounts (μg) and normalized concentrations (ng aMT6s/mg Creatinine) of melatonin metabolite (aMT6s) in urine of 55 volunteers exposed or sham-exposed to 30 min of digital mobile phone RF radiation just prior to bedtime.

	aMT6s (μg)		Normalized aMT6s Concentration (ng aMT6s/mg Creatinine)	
$n = 55$	Pre- Bedtime	Post- Bedtime	Pre-Bedtime	Post-Bedtime
Sham	1.9 ± 0.5	12.2 ± 1.0	7.7 ± 1.3	29.2 ± 2.0
Exposed	1.3 ± 0.2	13.3 ± 1.2	5.6 ± 0.6*	29.4 ± 1.9

*Value significantly less ($p = 0.037$, one-tailed) than the corresponding sham value: paired comparison.

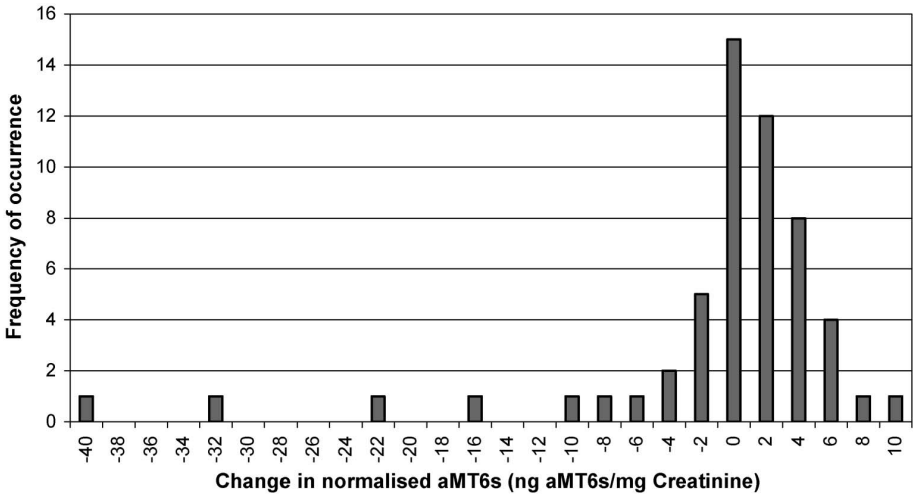

Figure 1. Histogram of differences in pre-bedtime normalized aMT6s on the two nights of urine collection (successive Sunday nights).

remaining 51 being normally distributed around zero. The actual Active/Sham normalized aMT6s values for the 4 individuals are as follows: 18.6/40.9; 7.4/23.4; 4.7/37.9; 3.9/46.9. If these four are eliminated from the analysis the change is non-significant ($p = 0.45$). These 4 individuals (3 female, 1 male) showed no common characteristics in responses to the demographics/electrosensitivity questionnaire and as Figure 2 reveals, no extreme differences in bedtimes between the two exposure conditions. Further, the actual bedtimes were close to the mean values reported above.

In the analysis of sleep architecture (Loughran et al. 2005), 5 participants were identified as suffering from some form of sleep apnoea. If these individuals were excluded from the analysis, the reduction in pre-bedtime normalized aMT6s is still significant ($p = 0.047$). None of the 'outliers' referred to above suffered from sleep apnoea.

Discussion

The total amount of melatonin metabolite (aMT6s) – the pre- and post-bedtime samples added together (Table II) – compares favourably with values quoted by others (Burch et al. 1999) and a range 4.1–24.2 μg by Kovacs et al. (2000). It is difficult to assess whether the average 27% reduction in pre-bedtime normalized aMT6s in the active relative to the sham condition is due to a relative small number of individuals, for whom the reduction is even larger, or is, in fact, spurious. A reduction of aMT6s of this magnitude needs to be commensurate with that possible after a delay in production of the order of 20 min (the biological half-life of melatonin: Brown et al. 1997). The 1st urine sample was collected within 5–10 min of cessation of the 30-min exposure period (0.6 h approximately). Participants were instructed to refrain from urinating after 20:00 h until the collection of the 1st sample at around 22:30–23:30 (3 h approximately). Even assuming the participants all urinated immediately prior to 20:00 h, that part of the sample capable of being influenced by the RF radiation was only approximately 0.6 h/3.0 h = 20% of the time (and hence of the urine collected, assuming steady urine flow). On the other hand, our previous study (Wood et al. 1998) reported an average time of melatonin onset in 92 determinations of 22:00 h (SD ± 1.9 h). The RF exposure would thus have tended to coincide with melatonin onset and thus the bulk of aMT6s would have been added to the urine in the hour or so immediately prior to collection. Melatonin onset times were shown in a previous study (Wood et al. 1998) to be quite stable for individuals. For example, the individual mean difference (± SD) between two nights one week apart 0.00 ± 1.0 h. Prior to onset the plasma melatonin level is essentially zero, rising to half maximal level in 2 h, approximately. However, even if the breakdown delay is built in, the reduction observed would only be possible if the aMT6s added to urine during the 30-min exposure were minimal or onset were delayed. Another possibility is that the rate of breakdown from melatonin to aMT6s is being reduced by RF emissions. Of these possibilities the delay in onset is perhaps the most likely (if it is indeed a real effect) and that the relatively small number of individuals 'responding' is a function of the timing of exposure relative to onset on a particular night. In a previous study (Wood et al. 1998) we presented evidence of roughly 25% of

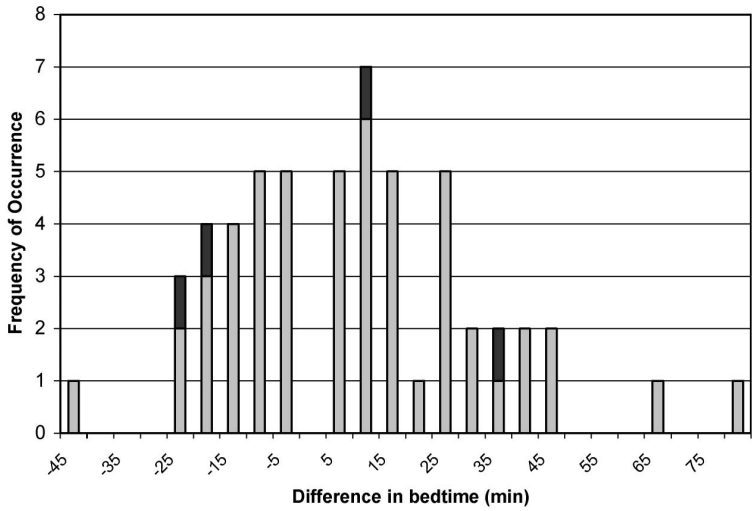

Figure 2. Histogram of differences in bedtime (time of commencement of polysomnographic record in min) on the two nights of urine collection (successive Sunday nights). Differences for the 4 outlying individuals in Figure 1 shown as dark bars.

participants responding to 50 Hz magnetic field exposure with a delay in onset, the remainder being unresponsive. It may be relevant to note that in addition to RF emissions from the phone handset, the Extremely Low Frequency magnetic fields, measured at up to 50 μT (Jokela et al. 2004) are of similar magnitude to those used in our previous studies (Wood et al. 1998, Keetley et al. 2001). However, the former exposure falls off rapidly with distance, but exposure was to the whole body in our previous studies.

In regard to the 4 individuals who were the outliers in this study, the normalized aMT6s values for the sham condition were towards the high extreme values of the study population. This could indicate that the natural melatonin onset time was earlier in these individuals and that the exposure occurred during a sensitive period, but in view of the small numbers involved, experimental artifact cannot be ruled out. The pre-bedtime normalized aMT6s value was actually higher than the post-bedtime value for the 4th individual's sham condition, but there were other (rare) instances (under both conditions) of the pre- and post-bedtime ratio being greater than unity. The total aMT6s (pre- and post-bedtime values added) was reduced by 25% for this individual by active exposure.

Finally, there is a possibility that exposure to sources of EMF or bright light in the period prior to coming to the laboratory could confound the results reported here. The differential design with a randomized order would tend to minimize these extraneous factors, but they cannot be ruled out. Since participants probably used the same form of transport to the laboratory on both sham and exposure evenings, some degree of consistency might be expected at least in the period immediately prior to arrival.

Conclusion

The total overnight melatonin secretion, as measured by the amount of urinary melatonin metabolite aMT6s is unaffected by exposure to emissions from a mobile phone handset for 30 min in the period just prior to sleep. A significant reduction in aMT6s relative to creatinine concentrations in pre-bedtime samples requires independent verification before a conclusion can be reached regarding these emissions leading to a delay in melatonin onset time, possibly in a sensitive sub-group of individuals.

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