NON-THERMAL EFFECTS AND MECHANISMS OF INTERACTION BETWEEN ELECTROMAGNETIC FIELDS AND LIVING MATTER

An ICEMS Monograph

Eur. J. Oncol. - Library Vol. 5

RAMAZZINI INSTITUTE

Edited by
Livio Giuliani and Morando Soffritti

European Journal of Oncology
Eur. J. Oncol. - Library Vol. 5

National Institute for the Study and Control of Cancer and
Environmental Diseases "Bernardino Ramazzini"
Bologna, Italy
2010

RAMAZZINI INSTITUTE

SPONSORS

International Commission for Electromagnetic Safety

National Institute for the Study and Control of Cancer and Environmental Diseases "Bernardino Ramazzini"

isbn
978-88-6261-166-4

pubblicazione
FIDENZA 2010

CONTENTS

Comparative assessment of models of electromagnetic absorption of the head for children and adults indicates the need for policy changes

Yueh-Ying Han*, Om P. Gandhi**, Alvaro DeSalles***,
Ronald B. Herberman****, Devra L. Davis*****

* Department of Epidemiology, Graduate School of Public Health, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

** Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, Utah, USA

*** Electrical Engineering Department, Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brasil

**** Chief Medical Officer, Intrexon Corporation, Bethesda, MD, USA

***** Georgetown University, Science, Technology and International Affairs, School of Foreign Service, Washington DC, USA and Founder, Environmental Health Trust

Abstract

Globally more than four billion phones are in use, with more than half of all users believed to be children and young adults. Over the past two decades, models of the human head have been devised based on imaging studies and used to estimate the extent and rate of radiation energy absorption to the brain, the Specific Absorption Rate (SAR). IEEE and ICNIRP SAR recommendations rest solely on avoiding thermal effects on the adult male head under conditions of a six minute long call and do not take into account the long-term cell phone use, the length of calls, non-thermal biological effects, the smaller size and greater physiological vulnerability and increased absorption to the heads of children and females. Currently recommended approaches by the IEEE calculate peak spatial average SAR for safety compliance testing of cell phones based on a physical model of an adult male head with an added 10 mm plastic spacer to model the ear (pinna). By incorporating such a spacer, the IEEE model assumes that the RF energy absorption in the ear (or pinna) may be treated like extremities of the body such as the legs and the arms that are not proximate to the brain. The 10 mm spacer artificially results in 2 to 4 times lower exposures to the head. Recent epidemiologic studies of adults from those few nations where cell phone use has been extensive for a decade or longer indicate significantly increased risk of a variety of brain tumors. These findings, together with the limitations of currently used head models and the growing use of phones by the young and females, indicate a clear and compelling need for improved, biologically-based

Address: Devra Lee Davis, PhD, MPH, Address: 328 Maryland Ave N.E., Washington, DC. USA
Tel. 412-897-1539 - Fax: 202-544-6631 - E-mail: devra.davis@gmail.com

models of the head in order to better estimate population-wide exposures of children and women to cell phones and provide the grounds for improved policies to reduce those exposures.

***Key Words*: health effects, mobile phones, Specific Absorption Rate (SAR), children and adults, radio frequency radiation, brain and cell phone.**

Introduction

Cell phone use has grown exponentially throughout the world in less than a decade. More than half of the world's population uses cell phones today as telephones as well as clocks, radio, video, and tools for exchanging information. Current technology of 2G and 3G phones operates in the microwave range, from 800 to 2450 megahertz (MHz). Standards for these phones rest on guidance developed by two non-governmental engineering-based groups, the Institute of Electrical and Electronics Engineers (IEEE) and International Commission on Non-Ionizing Radiation Protection (ICNIRP)[1, 2]. For compliance with IEEE and ICNIRP exposure limits, the quantification of exposure to the head, the 1 or 10 gram (g) Specific Absorption Rates (SAR), is based on a physical model of an adult male head with a 10 mm spacer at the ear, or pinna, to estimate radiofrequency (RF) thermal energy absorption that can take place in the course of a call with no accounting for the duration of the call assuming that it will not result in change in temperature of the brain. In the U.S., Canada, and most industrial nations, there is no independent review of these standards, monitoring of the cell phone manufacturers for compliance with these standards, or monitoring of cell phone use in real life.

A growing number of *in vitro* and *in vivo* studies have confirmed that both 2G and 3G signals at non-thermal levels are genotoxic[3, 4]. Potential mechanisms of such impact include changes in free-radical formation, alterations in electron conformation, and inhibition of proteins and other factors involved in DNA repair and synthesis. While molecular mechanisms for possible adverse effects have not been completely elucidated, energy absorption of higher frequency signals emitted by recently developed 3G, or even the new generation 4G cell phones, may result in greater biological effects. Based on these considerations, a growing number of national governmental agencies have issued precautionary advisories, urging that children avoid regular use cell phones next to their heads, restricting the marketing and development of cell phones for children, and recommending general methods for reducing direct exposure to the head of adults[5].

To complement such general precautions, this paper briefly reviews the underlying engineering and biology of RF signals associated with different generations of phones, synthesizes evolving evidence on the health effects of RF, clarifies and considers the strengths and limits of currently used models of the head used for testing phones, and summarizes efforts to promote precaution regarding the use of phones.

The changing nature of RF cell signals

Over the past four decades, cell phone types and uses have radically changed. The first generation, known as 1G, was a bulky cell phone introduced in the 1980s based on analog modulation with output power typically around 2 to 3 Watts (W). Examples of these systems are the Advanced Mobile Phone System (AMPS) in North America, Asia

Pacific, Russia, Africa and Israel in the frequency band between 800 and 900 MHz, and the Nordic Mobile Telephone (NMT) 900 system since 1986 in Scandinavia, Netherlands, Switzerland and Asia. The RF from 1G phone was presumed to produce mainly thermal effects, with any potential risks resulting from heating of the tissues.

The advanced generations of cell phones, namely 2G and 3G, employ higher data rates and a broader range of multimedia services and were launched in 1991 and 2001. Unlike 1G cell phones, the maximum radiated power was now controlled by the base station (cell tower or mast). The base station reduced the power emitted by 2G and 3G cellphones to a level that produces a good signal to noise ratio (SNR). These phones rely on digital modulation with mean (rms) output power typically around 250 or 125 mW (maximum 1-2W). Typical examples of these systems are: the North American Digital Cellular (NADC) system (824-894 MHz) since 1991 in USA; the Personal Communication Services (PCS) system (1850-1990 MHz) since 1996 in USA; the Global System for Mobile Communications (GSM) system (880-960 MHz) since 1991 in Europe and Asia Pacific; and the Digital Cellular System (DCS) 1800 (1710-1880 MHz) employed since 1993 in Europe. The modulation signals used in these digital systems are complex with the lowest rate of 217 Hz (e.g., GSM is encoded at 217 pulses/sec). This lower rate was reported to result in greater interaction with the biological tissues, inducing non-thermal effects and increased risks to living cells, even at low absorbed average powers[6]. Current 3G and 4G phones involve modulation with even lower minimum pulse rates and much higher data rates. As a result, 3G phones can result in greater cumulative average exposures, a result of the higher data rates.

Most contemporary cell phones use monopole or helix type antennas, which produce similar radiation patterns. The radiation pattern determines how the energy is distributed in the space. This can be represented by two planes that are orthogonal to each other, one is the electric field, the other is the magnetic field. When a monopole or helix antenna rests in a vertical direction and is unimpeded by any RF absorbing obstacle like the human head or body, it produces a nearly symmetrical pattern of RF around this antenna. In actual use about one half of the RF energy radiated by a cell phone is absorbed by the human head. The closer the cell phone is to the head the greater is the absorbed energy in the head tissues.

Biologic effects of non-ionizing radiation

Ionizing radiation (IR) is well known to have potent biological effects that break chemical bonds creating ions. This breakage of bonds results in diseases ranging from cancer to developmental and reproductive impairment, to death.[7] These biological impacts arises because 15% of the IR directly breaks ionic bonds at the backbone of DNA causing mutations that can lead to cancer; 85% of IR damage is caused by the creation of free radicals in the cell's cytoplasm near the DNA molecule, also resulting in DNA mutations, or through other mechanisms that are still being elucidated.

Non-ionizing radiation (NIR), found at all frequencies with energy levels too low to break chemical bonds from low-frequency electric power systems to microwave (MW) frequencies used by cell phones also produces biological effects when studied in cell cultures and in experimental animals. At low levels, equivalent to exposure from radiation from mobile phones, RF has been shown to result in damage to biological tissues, including both single and double DNA strand breaks, alterations in the permeability of the blood-brain barrier (BBB), oxidative stress, and damage to neural cells of the brain[8, 9].

Two mechanisms have been identified thus far to explain the variety of non-ionizing electromagnetic fields (EMFs) interactions with biological systems: thermal effects and non-thermal effects. Thermal effects arise directly from the increased movement of molecules results in tissue heating as a result of the absorption of EMFs in a dissipative medium. Absorption of energy at MW/RF frequencies is largely due to the motion of water dipoles and dissolved ions. At high frequencies (such as for the MW/RF band), tissues with high water content, such as occurs in the brains of young children, show electrical conductivity increasing with frequency. Thus, the net thermal response of the body will vary depending on SAR, ambient temperature, clothing, thermoregulatory system and physiological condition.

Non-thermal effects can result from direct interaction of the MW/RF fields on molecules or tissue components, changing electron conformation, altering stress proteins (previously known as heat shock proteins), immune-system function and having other impacts that remain to be clarified. Non-thermal effects are still not very well understood and their exact consequences on human health are still being investigated. Some reported non-thermal effects on tissue are biochemical and electrophysiological effects and can result in changes in the nervous, immune and cardiovascular systems, as well as in metabolism and hereditary factors[4, 10, 11].

In a pioneering research effort that created the widely used Comet Assay, Lai and Singh demonstrated that two hours of microwave radiation, comparable to that emitted by a cell phone, damaged DNA of the rat brain[12]. A European study team of a dozen collaborators under the aegis of REFLEX [Risk Evaluation of Potential Environmental Hazards from Low Energy Electromagnetic Field (EMF) Exposure Using Sensitive in vitro Methods], found evidence that low (non-thermal) energy levels of RF exposure induced double strand breaks in DNA of cells exposed to between 0.3 and 2 W/kg[13]. Although the mechanism(s) underlying such non-thermal effects of NIR remains unclear, it seems quite plausible, as with the cancer-promoting effects of inflammatory lesions, that mutagenic damage to DNA could be induced by generated free radicals. In contrast, many other studies of non-thermal or thermal effects of RF issue have yielded no evidence of DNA damage. But, the great preponderance of these negative studies have not reflected independent research but resulted from studies directly funded by the cell phone industry[14].

Current SAR calculations rest solely on avoiding thermal impacts. In principle, as the newer generation of digital phones radiate lower mean power in comparison to the analogue phones, the risk associated with the heating of tissues should be correspondingly reduced. However, most mobile communication systems are pulse-like in nature and modulated at low frequencies with high data rates. As a result, these newer systems can induce low-levels of currents in the brain tissues that have been linked with a variety of non- or thermal effects, e.g., BBB alterations, single and double strand DNA breaks, chromosomal aberrations, etc., at RF energy levels substantially below the thermal threshold.

Despite the growing industry-independent evidence that NIR has a range of biological impacts, intense controversy surrounds the interpretation of the limited available public health investigations regarding risk for cancer or other chronic diseases. Human studies on both cancer and non-cancer impacts of NIR are inconsistent for reasons that have been thoroughly discussed by a number of authors[15].

Epidemiologic studies

The biology and epidemiology of the often lethal cancer of the brain is complex. It is unreasonable to expect to be able to detect an increased risk of brain tumors in less than a decade, because brain tumors are known to have latencies that can be between a decade to four decades long[16]. Recently several authors have produced meta-analyses that show that only when studies have followed people for a decade is there evidence of increased risk (Table 1).

For more than a decade, Hardell and his colleagues conducted a series of studies in Sweden, a country where proportionally more of the population has heavily used cell phones for a longer period of time than in many other industrialized nations. Regarding acoustic neuroma (AN), the Swedish group reported an 2.7 to 5.1 fold increased risk of AN for those regularly using an analog cell phone for five years or more compared to those who never or rarely used a cell phone[17, 29]. Hardell's team also found long-term analogue cell phone use significantly increased the risks of meningioma and astrocytoma[22, 29]. Recently, Hardell and Carlberg found that persons who had used cell phones for 10 years or more also had the highest risk for astrocytoma. This study also included persons who had begun to use cell phones before age 20. Cases with first mobile phone use younger than 20 years age had five times more brain cancer for 1 or more years of use (OR=5.2, 95% CI=2.2-12). For AN, the highest risk was found for greater than 10 years of ipsilateral mobile phone use (OR=3.0, 95% CI=1.4-6.2)[30].

The International Agency for Research on Cancer (IARC) began an international collaborative case-control study on cell phone use and the incidence of brain tumors in 13 countries in 1997 (the INTERPHONE study). Among six INTERPHONE reports from different countries, which included persons who had used phones episodically for less than a decade, none reported a relationship between cell phone use and AN[18-20, 31-33]. They did not report any significant relationship between long term cell phone use and glioma, meningioma or other brain tumors[21, 24, 25, 27, 28]. However, the recently published Interphone study found that the heaviest cell phone users, cumulative call time $\geq$ 1640 hours have increased risk of glioma (OR=1.40, 95% CI=1.03-1.89) and meningioma (OR=1.15, 95% CI=0.81-1.62)[34]. Brain tumor risk was not found to be higher among those who use cell phone less frequently.

The lack of an observed association between published studies of cell phone use and risk for malignant or benign tumors in other published studies could reflect a number of methodological limits of study design. Most of these negative studies involved relatively short time periods of cell phone use, infrequent use of cell phones, or a small number of cases. In an effort to refine evaluation of the issue, studies have been carried out that separate out extent and type of cell phone use, including side of the head on which phones are typically used. The Hardell group found a consistent pattern of an association between ipsilateral AN and cell phone use providing that there was a 10-year latency period or longer (OR=2.4, 95% CI = 1.1-5.3)[23]. Two additional studies from other investigators in the Nordic region[19, 20] produced similar results. A study used interphone protocol that poold data from 5 North European countries similarly found an increased glioma risk after a decade of use for ipsilateral cell phone exposure (OR=1.4, 95% CI=1.0-1.9)[35]. A significant excess risk for reported ipsilateral phone use to the tumor was also found for glioma regardless of the duration of cell phone use[26].

A recent meta-analysis of studies produced by a team from California and Korea has corroborated this analysis, noting that the Hardell's work consistently reflects high

Table 1 - Summary of published articles on brain tumors and long term (≥ 10 years) cell phone use

Study	Population	Period	Study type	No. cases	No. controls	OR (95% CI)	Cell phone exposure
Acoustic Neuroma							
Hardell *et al.*, 2002[17]	Sweden	2000-2002	Case-control	46	26	1.8 (1.1-2.9)	regular analogue phone use
Christensen *et al.*, 2004[18]	Denmark	2000-2002	Case-control	2	15	0.2 (0.04-1.1)	regular use
Lönn *et al.*, 2004[19]	Sweden	1999-2002	Case-control	14	29	1.8 (0.8-4.3)	regular use
				12	15	3.9 (1.6-9.5)	ipsilateral exposure
Schoemaker *et al.*, 2005[20]	4 Nordic countries and UK	1999-2004	Case-control	47	212	1.1 (0.7-1.5)	regular use
				23	72	1.8 (1.1-3.1)	ipsilateral exposure
Schüz *et al.*, 2006[21]	Denmark	1982-2002	Cohort	28	42.5	0.7 (0.4-1.0)*	regular use
Hardell *et al.*, 2006[22]	Sweden	1997-2003	Pooled case-control	19	84	2.2 (1.4-3.8)	regular analogue phone use
				1	18	0.6 (0.1-5.0)	regular digital phone use
Hardell *et al.*, 2008[23]	Sweden		Meta-analysis	83	355	1.3 (0.6-2.8)**	regular use
				53	167	2.4 (1.1-5.3)****	ipsilateral exposure
Glioma							
Christensen *et al.*, 2005[24]	Denmark	2000-2002	Case-control	6****	9	1.6 (1.4-6.1)	regular use
Lonn *et al.*, 2005[25]	Sweden	2000-2002	Case-control	22	33	0.9 (0.5-1.6)	regular use
				14	15	1.8 (0.8-3.9)	ipsilateral exposure
Hepworth *et al.*, 2006[26]	UK	2000-2003	Case-control	48	67	1.1 (0.7-1.7)	regular use
Schüz *et al.*, 2006[27]	Germany	2000-2003	Case-control	12	11	2.2 (0.9-5.1)	regular use
Lahkola *et al.*, 2008[28]	5 European countries		Case-control	143	220	0.9 (0.7-1.3)	regular use
				77	117	1.4 (1.0-1.9)	ipsilateral exposure

(continued)

Table 1 - Summary of published articles on brain tumors and long term ($\geq$ 10 years) cell phone use

Study	Population	Period	Study type	No. cases	No. controls	OR (95% CI)	Cell phone exposure
Meninglioma							
Lönn *et al.*, 2005[25]	Sweden	2000-2002	Case-control	8	32	0.7 (0.3-1.6)	regular use
				4	15	1.4 (0.4-4.4)	ipsilateral exposure
Christensen *et al.*, 2005[24]	Denmark	2000-2002	Case-control	6	8	1.0 (0.3-3.2)	regular use
Hardell *et al.*, 2006[22]	Sweden	1997-2003	Pooled case-control	34	84	1.6 (1.0-2.5)	regular analogue phone use
				8	18	1.3 (0.5-3.2)	regular digital phone use
Schüz *et al.*, 2006[27]	Germany	2000-2003	Case-control	5	9	1.1 (0.4-3.4)	regular use
Lahkola *et al.*, 2008[28]	5 European countries		Case-control	42	130	0.9 (0.6-1.3)	regular use
				21	73	1.0 (0.6-1.7)	ipsilateral exposure
Astrocytoma							
Hardell *et al.*, 2006[29]	Sweden	2000-2003	Case-control	40	40	3.7 (2.0-7.0)	regular analogue phone use
				16	18	2.2 (0.8-6.5)	regular digital phone use
All Malignant Brain Tumor							
Hardell *et al.*, 2006[29]	Sweden	2000-2003	Case-control	48	40	3.5 (2.0-6.4)	regular analogue phone use
				19	18	3.6 (1.7-7.5)	regular digital phone use

* Standardized incidence ratio was calculated based on observed and expected numbers
** Based on 4 case-control study (Lönn et al 2004, Christensen et al. 2004, Schoemaker et al. 2004, and Hardell et al., 2006)
*** Results from a Meta-analysis, based on three case-control studies (Lönn et al., 2004, Schoemaker et al., 2005 and Hardell et al., 2006)
**** low-grade glioma

quality methods and design. The researchers examined 465 articles published in major journals and focused on 23 studies involving 37,916 participants. In eight of the studies – those that were conducted with the most scientific rigor – cell phone users were shown to have a 10% to 30% increased risk of all types of tumors studied compared with people who rarely or never used cell phones (OR=1.2, 95% CI=1.0-1.3). The risk was highest among those who had used cell phones for 10 years or more[36].

The results of the entire literature on epidemiology and cell phone use remain controversial, because most studies suffer from a number of methodological shortcomings including: insufficient statistical power to detect an excess risk of brain tumors; reliance on small populations; short-term exposure periods; problems in recollection of past practices and difficulty in characterizing changing exposures throughout a lifetime in large populations. As a number of researchers have suggested, retrieving billing records from cell phone network providers to obtain cumulative duration and frequency of cell phone use and corroborating personal interview would provide the capability to validate self-reported cell phone exposure in future studies[37]. Assuring independent funding for future research will also be critical, given the widely reported biases associated with the design and interpretation of industry-funded studies to date.

Regarding short-term health impacts from RF exposure such as insomnia, impairment of short-term memory, headache, alteration of EEG and other behavioral problems, evidence has been fairly consistent that such effects are worsened in longer term cell phone users[38, 39]. Whether these relatively benign perturbations signal the likelihood that more serious health impacts will occur after longer-term RF exposure is a matter of critical importance for future studies.

Models of the head used to evaluate compliance with safety standards

Given the concerns that have been raised from the biological and epidemiological studies, it is important to establish standards for RF exposures from cell phones that incorporate the best scientific information regarding differences in the heads of people of various sizes, genders and ages. Children's skulls are thinner and their brains are less dense and more fluid, making them more vulnerable than adults to RF signals. Size alone affects absorption. In addition, other physiological properties such as permittivity, electrical conductivity and density also affect transmission and absorption of RF signals, as does myelination of the nerves of the brain, which is not complete until the early to mid-twenties[40].

The relative permittivity of a material under given conditions is measuring the extent to which it concentrates lines of flux. The relative permittivity of any material is expressed as the ratio of the amount of stored electrical energy when a potential is applied, relative to the permittivity of the vacuum. The relative permittivity or dielectric constant of the air is 1, while that of an adult brain is around 40 and that of a young child's brain is higher closer to 60 to 80[41]. This means that peak SAR in a child's head may be 50% to 100% higher than that for an adult[42].

Conductivity and absorption of RF signals are a function of the dimensions and dielectric properties of the tissues that are directly exposed, as well as their neural density, with nerve cells being much more active than bone, hair, or skin. Conductivity is a parameter relating the electric field to the current density. For the same intensity of electric field, the increase in the conductivity will increase the current density and the

SAR. The absorption of RF energy will then increase, resulting in greater electromagnetic dissipation. Based on the measurements described by Peyman *et al*, the permittivity and the conductivity in the children's head tissues are estimated to be around 20% greater than in adults[41, 43, 44].

The combination of both effects, the increase in the concentration of the electric field due to the increase in the electrical permittivity together with the increase of dissipation of RF/MW energy due to the increase in the conductivity, can result in a substantial SAR increase in the children's head in comparison to the adults.[42, 43]

The weight and size of the tissue being used for estimating the SAR will also affect assessments, with exposures averaged over 1 gram of the head being more stringent than those averaged over 10 grams of the whole body, as the latter involves bone and tissue of more varying electrical conductivities and mass densities than the former. The process of myelination of the brain protects nerves from damage by surrounding them with myelin sheaths, with myelination incomplete until the MID-205 could be yet another factor of concern for children and young adults using cellphones.

Recently, the use of cell phones by young and children has been modeled through a variety of simulations; some based on magnetic resonance imaging (MRI) others based on computerized tomography (CT) scans. Some studies have produced SAR simulations for the heads of adults [45, 46], while others took children into consideration[42-44]. A range of results was obtained (Table 2). In the Utah Model[47], the children's head was based on a scaled adult model and a SAR increase (compared with adult) of up to 153% was obtained.

In Schonborn's study, the head model was based on MRI using similar electromagnetic parameters as those for adults, and no significant differences between adult and children SAR results were observed[54]. In another study, the head model was approximated by spheres considering some variation of the electromagnetic parameters, and an increase of around 20% in the calculated SAR was shown[55].

Using a scaled model for the children's head with adult electromagnetic parameters, no significant variation for the average SAR in the whole head was observed, and when considering the brain, an increase of around 35% in the SAR was calculated[51]. In De Salles's study, a 10 year old child head was developed based on CTI from a healthy boy[43]. The physical and the electromagnetic parameters, such as the permittivity, the equivalent conductivity and the density were fitted to this age. SAR results around 60% higher than those simulated for the adults were observed for the children with fitted parameters.

Wiart and his colleagues developed child head models based on MRI. The combined results of these studies indicate that the maximum SAR in 1 g of peripheral brain tissues of the child models aged between 5 and 8 years is about two times higher than in adult models[52]. More recently in an internal IT'IS Foundation Report, Kuster *et al.*[53] report that spatial peak SAR of the CNS tissues of children is "significantly larger (~2x) because the RF source is closer and skin and bone layers are thinner".

In all models used, it is readily apparent that smaller heads will absorb proportionally more RF than larger heads, but size is not the only property of interest in estimating differential SAR absorption of younger and older brains. Neuro-development of the brain is an exquisitely complex process that occurs at a more rapid pace in young children than in adults. As a result, even if exposures were equal in persons of all ages, the brains of children are more vulnerable than those of adults. In 1996, Gandhi published a report modeling the greater absorption of RF into the brain of a child compared to that of an adult[47]. Subsequent work refined this analysis, taking into account a range of

Table 2 - Some tissue-classified models of the head and the whole body for estimating radiofrequency absorption of humans

Author, Year	Model	Height, Weight, Sex	Derived From	Voxel Size	# of Tissues, Organs	Percentage SAR Underestimation	Cumulative Percentage SAR Underestimation for Child	Comments
Gandhi *et al.*, 1996 [47]	Utah Model	1.75 m ht, 71 kg wt; also scaled models of 5- and 10-year old children	MRI scans	1.974x1.974x2.9 mm for the model of the adult; smaller cell sizes for models of children	32	<153%	<383%	Child's heads scaled from adult's head
Dimbylow, 1998 [45]	NORMAN*	1.7 m ht, 70 kg wt to correspond to "reference man" ICRP23[45]	MRI scan single subject	2x2x2 mm, 2.04x2.04x1.95 mm	37			
Peyman *et al.*, 2001 [41]						40%	40%	Permittivity & conductivity in children is 60-80 compared to adult's 40
Gandhi and Kang, 2002 [42]	Utah Model	MRI-derived model of the adult and scaled models** of 5- and 10-year old children	MRI scans	Different scaling factors for the head and the rest of the body		50% + >100% from 10 mm spacer + 80% for electrical parameters	~200% @ 1900 MHz; 144% @ 835 MHz	10% smaller head results in 50% underestimation of SAR
Kang and Gandhi, 2002[48]		model of the adult	MRI scans				15%/mm of spacer	
Wang and Fujiwara, 2003[49]	Japanese Adult Model	Scaled Models of 7- and 3-year old children adult	MRI scans of the					Multiple studies find children absorb more radiation than adults. See also references 42, 47, 50-52, and 54.

(continued)

Table 2 - Some tissue-classified models of the head and the whole body for estimating radiofrequency absorption of humans

Author, Year	Model	Height, Weight, Sex	Derived From	Voxel Size	# of Tissues, Organs	Percentage SAR Underestimation	Cumulative Percentage SAR Underestimation for Child	Comments
Gandhi and Kang, 2004 [50]	Specific-anthropo-morp-hic phantom (SAM)	Plastic head-shaped phantom with a plastic spacer to represent the pinna	90 th percentile head size of military personnel		Filled with homogenous fluid	Underestimates SAR by a factor larger than 2	Not tested for the size of a child's head	Use of a 6-10mm thick plastic spacer makes it impossible to measure the highest SAR for the pinna
Martinez-Burdalo *et al.*, 2004 [51]		Child	Scaled model from adult electrical parameters				35%	As head size decreases, the percentage of energy absorbed in the brain increases
Fernandez *et al.*, 2005 [44]	10 years old Brazilian Model	10 year old child (1.2 m height, 35 kg, male)	102 CT scans	0.946 mm x 2.044 mm x 1.892 mm (3.10 mm^3)	10			Permittivity & conductivity of 10 year old
De Salles *et al.*, 2006 [43]	10 years old Brazilian Model	10 year old child (1.2 m height, 35 kg, male)	102 CT scans	0.946 mm x 2.269 mm x 1.601 mm (3.43 mm^3)	10	60%		permittivity & conductivity of 10 year old
Wiart *et al.*, 2008 [52]		Child's Head, 5 to 8 years old	MRI scans			100% (2x)		Antenna closer to skin and bone layers are thinner; penetration of radiation is twice as deep in child
Kuster *et al.*, 2009 [53]		Child				>100% CNS tissues		SAR of CNS of children ~twice that for adults

* NORMAN=NORmalized Man

** Scaled models of 5- and 10-year old children derived from the Utah Model using external dimensions typical of children from Geigy Scientific Tables (C. Lentner-Geigy Scientific Tables, Vol. 3, CIBA-Geigy, Basil, Switzerland, 1984).

anatomic differences between adults and children, including conductivity, density and dielectric constants. Gandhi and Kang reported that models with a head that was only about 10% smaller in size could have more than 50% greater SAR with two different antenna lengths, with proportionally deeper penetration of SAR[42]. This work also showed that incorporating a plastic ear model or pinna with a 10 mm spacer gave artificially lowered SAR-values, which are up to two or more times smaller than for realistic anatomic models, as a result of the larger distance to the absorptive tissues. The higher dielectric constant and conductivities likely for younger subjects will result in still higher SAR (up to 80% more) for children.

The peak 1-g body tissue SAR for the smaller head sizes calculated using the widely accepted Finite-Difference Time-Domain (FDTD) computational EMFs method can be up to 56% higher at 1900 MHz and up to 20% higher at 835 MHz compared to the larger models. For brain tissue, the proportionality was even higher where the peak 1-g SAR for the smaller model was up to 220% higher at 1900 MHz and up to 144% higher at 835 MHz of the SARs of the larger models. Similar to the results reported in the earlier 1996 paper for head models of adult and children, these latter results confirmed that there is a deeper penetration of absorbed energy for the smaller head models e.g. the children compared to that for the larger head models representative of adults.

In 2004, a IEEE Standards Coordinating Committee introduced a standard anthropomorphic mannequin (SAM) Model, with a 6-10 mm thick plastic spacer instead of "pinna" for determination of SAR of mobile phones for compliance testing against IEEE and ICNIRP Safety Guidelines (IEEE, 2003). That same year, Gandhi and Kang demonstrated that the "SAM model" with plastic spacer used for compliance testing (preferred by industry) gives SARs that grossly underestimate exposures[50]. In two different published studies, the use of plastic spacers results in an underestimation of the SAR by up to 15% for every additional millimeter of thickness of such spacers[48, 50]. Thus, the SAR obtained for SAM is up to two or more times smaller than for the anatomic models of the adult head. When other developmental variables are taken into account, this underestimation is even higher for exposure to the smaller heads of the children.

A modified SAM model with a lossy pinna similar to living tissue for which 1- and 10-g SARs are relatively close to those for anatomic models, could remedy this systematic underestimation of exposure of the children by using a fluid of higher conductivity than that currently used for compliance testing[42]. Without this correction, current IEEE limits[56] effectively allow RF that may be 8-16 times higher[50] than those permitted by previous IEEE guidelines[56, 57]. This is also due to increasing the SAR limit in the pinna from 1.6 W/kg for any 1-g of tissue to 4.0 W/kg for a larger 10-g of tissue that was originally suggested to apply only to the extremity tissues for the arms and the legs[57, 58].

In fact, multiple studies have reported that the brains of young children absorb more radiation compared to those of adults[43, 47-49, 51-53]. As the brains of children lack neural integration and are not fully myelinated until the twenties, the impact of such greater absorption may be considerable. In addition, this differential absorption of the brain may well render children more vulnerable to the development of both benign and malignant brain tumors, a point indicated in the review of this subject by the National Research Council[59]. Studies by Wiart for French Telecom published last year[52] and other work by Kuster[60] confirmed that a given signal is absorbed about twice as deeply into the bone marrow of the head and cortex of a child in contrast with that of an adult, even though systemic absorption may not differ substantially. A series of papers by De Salles also offers important modeling information regarding the increased vulnerability of a child's

Table 3 - Summary of the results confirming that children absorb more radiated electromagnetic energy of the cell phones resulting in higher specific absorption rate (SAR) as compared to adults

Author, Year	Highlights of results
Gandhi *et al.*, 1996 [47]	Deeper penetration of absorbed energy for models of 10- and 5-year old children; peak 1-g SAR for children up to 53% higher than adults.
Gandhi and Kang, 2002 [42]	Deeper penetration of absorbed energy for smaller heads typical of women and children; peak 1-g SAR for smaller heads up to 56% higher than for larger heads.
Wang and Fujiwara, 2003 [49]	Compared to peak local SAR in the adult head, we found “a considerable increase in the children’s heads” when we fixed the output power of radiation.
Martinez-Burdalo *et al.*, 2004 [51]	As head size decreases, the percentage of energy absorbed in the brain increases; so higher SAR in children’s brains can be expected.
DeSalles *et al.*, 2006 [43]	The 1-g SAR for children is about 60% higher than for the adults.
Wiart *et al.*, 2008 [52]	1-g SAR of brain tissues of children is about two times higher than adults.
Kuster *et al.*, 2009 [53]	Spatial peak SAR of the CNS of children is “ significantly larger (~2x) because the RF source is closer and skin and bone layers are thinner”; “ bone marrow exposure strongly varies with age and is significantly larger for children(~10x)”

head[43]. Based on CT images of a 10 year old boy, these models confirm the greater absorption of the child and add further support regarding the need to eliminate the plastic spacer at the ear or pinna in estimating exposures to children. A summary of the results confirming that children (and smaller heads typical of women) absorb more radiated energy of cell phones resulting in higher SAR is given in Table 3.

Implications of modeling limitations for current standards

Both the IEEE and ICNIRP guidelines are based only on short-term EMFs exposure and long-term EMFs exposures are not considered. Please refer to page 496[2]:

“Induction of cancer from long-term EMFs exposure was not considered to be established, and so these guidelines are based on short-term, immediate health effects such as stimulation of peripheral nerves and muscles, shocks and burns caused by touching conducting objects, and elevated tissue temperatures resulting from absorption of energy during exposure to EMFs. In the case of potential long-term effects of exposure, such as an increased risk of cancer, ICNIRP concluded that available data are insufficient to provide a basis for setting exposure restrictions, although epidemiological research has provided suggestive, but unconvincing, evidence of an association between possible carcinogenic effects and exposure at levels of 50/60 Hz magnetic flux densities substantially lower than those recommended in these guidelines”.

The increase in the SAR in the whole head, between the adult and the child, is expected due to the reduced dimensions in the child head, as well as the higher values of the permittivity and of the electrical conductivity of the child brain tissues. Also, children's skulls are thinner than those of adults, and therefore less resistant to radiation.

Another concern is that only thermal effects of RF are considered when estimating the SAR. However, since most mobile communication systems now are pulse-like in nature, modulated at low frequencies, such as in 2G and 3G (e.g., the GSM, UMTS, CDMA, TDMA systems), they are able to induce pulses of currents in the brain tissues and this can result in some low level non-thermal effects, e.g., BBB alterations, single and double strand DNA breaks, chromosomal aberrations, etc., at RF energy levels substantially below the thermal threshold. Several papers and reports have already shown adverse health effects at exposure levels well below the thermal limits[4, 6, 12, 13, 61]. Further epidemiological studies have shown a many-fold increase in risk for malignant brain tumors, with a larger than 10 years latency period for long-term mobile phone and cordless phone users[23]. As a substantial percentage of the population now uses mobile phones for a long time during each day and for several years, operating the antenna very close to their head, then this exposure can not be classified as short term and effectively may represent a serious risk for their health.

Future research needs

There is a need for exposure assessment of juveniles, children, pregnant women and fetuses from personal wireless devices (the wireless devices considered here are the cell phones, wireless PCs and text messaging devices), waist and pocket-mounted devices since mostly adult male models have been considered to date. These studies will focus on development and exposure quantification of anatomic models of several heights and weights of men, women and children of various ages as well as pregnant women and fetuses.

There is an urgent need for characterization of microwave radiated fields from the currently used multi-frequency, multi-element base station antennas; identification of exposed individuals and their locations e.g. school children, building maintenance personnel, etc. There is a paucity of data in regard to radiated electromagnetic fields and the daily variation in time for the newer 4-6 element or more collocated base station antennas and the exposures these antennas entail for the school children and the civilian population living close to such antennas.

An updated survey is needed of the civilian exposure to microwave electromagnetic fields strengths in the U.S. due to the rapidly expanding wireless infrastructure in the last 10-15 years. The last survey involving selected 15 metropolitan areas and mostly focused on VHF and UHF TV stations was reported back in 1980.[62] This data is totally out of date at the present time.

An expert (non-industry dominated) evaluation of the current IEEE and ICNIRP RF/microwave safety standards in the light of more recent biological experiments is also critical. All of the current safety standards are based on extrapolation from acute short-term exposures and do not account for the modulated signals used in cell phones and other personal wireless devices.

Discussion

The summary of modeling research presented here indicates three major shortcomings of the current IEEE and ICNIRP approaches: 1) the assumption that only thermal effects can occur is not valid. There is growing evidence from in vitro and in vivo studies indicating that RF exposures at levels not known to induce thermal effects commonly encountered today have a range of biological effects, affecting production of free radicals, permeability of the BBB, expression of in heat shock proteins, and direct damage to DNA, as indicated by the comet assay and a variety of in vitro measures of genotoxicity; 2) properties of the head models currently used fail to take into account differences in dielectric constant and conductivity and improper modeling of the pediatric brain, as well as developmental differences such as myelination between the young and older brains; 3) the assumptions as to typical use patterns used in setting these standards, with a six minute average call time, do not reflect current patterns, according to reports from the cell phone industry, where monthly use can easily top 2000 minutes with many calls well in excess of 6 minutes.

Excepting the occasional advertisement, there is no publicly accessible, independently confirmable, information on the details of rapidly expanding markets and uses of cell phones, which makes the development of standards especially challenging. Cell phones are used by many people for much of their waking hours, having replaced traditional phones, alarm clocks, newspapers, radios, global positioning devices, videocameras and televisions.

Regarding young children, we do not know the typical practice of the young at this point, because those behaviors are changing rapidly. However, we do know school districts are being urged to adopt cell phones for all middle school students as learning tools. This may well be an excellent idea for the purposes of learning, providing that phones are not used and held directly to the developing brain. Whether the use of cell phones as phones proves a potential hazard to the long-term health of the pediatric brain is an issue that merits serious attention. Radiation compliance standards for operation of cell phones are based exclusively on adult male models of the head. Emerging research indicates that long-term heavy users of cell phones face a doubled risk of several forms of brain tumors and risks may well be greater for those who begin regularly using phones before age 20. In light of these facts, the European Environment Agency and several other national advisory groups have adopted a precautionary approach to keep cell phone exposure to a minimum through use of ear-pieces and speaker phones, wired headsets, and to urge that children generally not use cell phones.

To enhance the ability to protect public health and foster better design of this widely used technology, we advise a three-pronged approach: major studies should be undertaken to construct and validate gender and age-appropriate head models further. More research is needed to identify and evaluate the mechanisms through which non- or thermal effects of RF arise and to determine more definitively the extent of health risks from long term use of cell phones, particularly by children. While that work is proceeding, precautionary policies should be advanced to limit potential harm to the developing brain. This should include consideration of directional antennas designed to send signals away from the head since the tissues absorb almost all of the energy radiated in the direction of the head anyway. Responsible public health authorities around the world should disseminate warnings for cell phone users such as those advocated recently in France, Finland and Israel. This involves advising children and their parents along with the young to make only short and essential calls, to use text messaging when possible, to use always hands free kits and wired headsets, and maintain the antenna far away from their body during the calls. Given the prevalence of this revolutionary technology, some evidence of its chronic toxicity, and the lack of solid information regarding its potential hazards to humans, it is important that major independent, multi-disciplinary research programs be carried out to study and monitor the long-term impact of RF exposures.

Acknowledgement

Support for this work was provided in part by grants from the National Institute of Environmental Health Science, the Heinz Endowments, the Jennie Zoline Foundation, the Environmental Health Trust, and center grants from the National Cancer Institute to the University of Pittsburgh Cancer Institute. The authors declare that they have no competing interests. Constructive comments have been provided by Lloyd Morgan and Allan Frey.

References

1. IEEE. ANSI/IEEE C95.1-1992-safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz. 1992.
2. ICNIRP. International Commission on Non-Ionizing Radiation Protection (ICNIRP) - Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys 1997; 74: 494-522.
3. The BioInitiative Working Group. BioInitiative Report: a rationale for a biologically-based public exposure standard for electromagnetic fields. www.bioinitiative.org.
4. Ruediger HW. Genotoxic effects of radiofrequency electromagnetic fields. Pathophysiology 2009; 16(2-3): 89-102.
5. IEGMP. Independent Expert Group on Mobile Phones, Report of the group (The Stewart Report): mobile phones and health. http://www.iegmp.org.uk/report/index.htm.
6. Salford LG, Brun AE, Sturesson K, *et al.* Permeability of the blood-brain barrier induced by 915 MHz electromagnetic radiation, continuous wave and modulated at 8, 16, 50, and 200 Hz. Microsc Res Tech 1994; 27(6): 535-42.
7. ATSDR. Agency for Toxic Substances and Disease Registry. Summary of health effects of ionizing radiation, toxicological profile for ionizing radiation. http://www.atsdr.cdc.gov/toxprofiles/tp149.html.
8. Nittby H, Brun AE, Eberhardt J, *et al.* Increased blood-brain barrier permeability in mammalian brain 7 days after exposure to the radiation from a GSM-900 mobile phone. Pathophysiology 2009; 16(2-3): 103-12.
9. Salford LG, Brun AE, Eberhardt JL, *et al.* Nerve cell damage in mammalian brain after exposure to microwaves from GSM mobile phones. Environ Health Perspect 2003; 111(7): 881-3; discussion A408.
10. Moseley H. Non-Ionizing Radiation - Biological Effects of Microwaves and RF. Medical Physics Handbooks 18, 1988: 38-61.
11. Bernhart JH. Non-Ionizing radiation safety: radiofrequency radiation, electric and magnetic fields physics on medicine and biology. Phys Med Biol 1992; 37: 807-44.
12. Lai H, Singh NP. Single- and double-strand DNA breaks in rat brain cells after acute exposure to radiofrequency electromagnetic radiation. Int J Radiat Biol 1996; 69(4): 513-21.
13. REFLEX. Final report. Risk evaluation of potential environmental hazards from low frequency electromagnetic field exposure using sensitive in vitro methods. http://www.itis.ethz.ch/downloads/REFLEX_Final%20Report_171104.pdf
14. Huss A, Egger M, Hug K, *et al.* Source of funding and results of studies of health effects of mobile phone use: systematic review of experimental studies. Environ Health Perspect 2007; 115(1): 1-4.

15. Kundi M. The controversy about a possible relationship between mobile phone use and cancer. Environ Health Perspect 2009; 117(3): 316-24.
16. Hardell L, Carlberg M, Soderqvist F, *et al.* Long-term use of cellular phones and brain tumours: increased risk associated with use for > or =10 years. Occup Environ Med 2007; 64(9): 626-32.
17. Hardell L, Hallquist A, Mild KH, *et al.* Cellular and cordless telephones and the risk for brain tumours. Eur J Cancer Prev 2002; 11(4): 377-86.
18. Christensen HC, Schuz J, Kosteljanetz M, *et al.* Cellular telephone use and risk of acoustic neuroma. Am J Epidemiol 2004; 159(3): 277-83.
19. Lonn S, Ahlbom A, Hall P, *et al.* Mobile phone use and the risk of acoustic neuroma. Epidemiology 2004; 15(6): 653-9.
20. Schoemaker MJ, Swerdlow AJ, Ahlbom A, *et al.* Mobile phone use and risk of acoustic neuroma: results of the Interphone case-control study in five North European countries. Br J Cancer 2005; 93(7): 842-8.
21. Schuz J, Jacobsen R, Olsen JH, *et al.* Cellular telephone use and cancer risk: update of a nationwide Danish cohort. J Natl Cancer Inst 2006; 98(23): 1707-13.
22. Hardell L, Carlberg M, Hansson Mild K. Pooled analysis of two case-control studies on use of cellular and cordless telephones and the risk for malignant brain tumours diagnosed in 1997-2003. Int Arch Occup Environ Health 2006b; 79(8): 630-9.
23. Hardell L, Carlberg M, Soderqvist F, *et al.* Meta-analysis of long-term mobile phone use and the association with brain tumours. Int J Oncol 2008; 32(5): 1097-103.
24. Christensen HC, Schuz J, Kosteljanetz M, *et al.* Cellular telephones and risk for brain tumors: a population-based, incident case-control study. Neurology 2005; 64(7): 1189-95.
25. Lonn S, Ahlbom A, Hall P, *et al.* Long-term mobile phone use and brain tumor risk. Am J Epidemiol 2005; 161(6): 526-35.
26. Hepworth SJ, Schoemaker MJ, Muir KR, *et al.* Mobile phone use and risk of glioma in adults: case-control study. BMJ 2006; 332(7546): 883-7.
27. Schuz J, Bohler E, Berg G, *et al.* Cellular phones, cordless phones, and the risks of glioma and meningioma (Interphone Study Group, Germany). Am J Epidemiol 2006; 163(6): 512-20.
28. Lahkola A, Salminen T, Raitanen J, *et al.* Meningioma and mobile phone use—a collaborative case-control study in five North European countries. Int J Epidemiol 2008; 37(6): 1304-13.
29. Hardell L, Carlberg M, Mild KH. Case-control study of the association between the use of cellular and cordless telephones and malignant brain tumors diagnosed during 2000-2003. Environ Res 2006a; 100(2): 232-41.
30. Hardell L, Carlberg M. Mobile phones, cordless phones and the risk for brain tumours. Int J Oncol 2009; 35(1): 5-17.
31. Takebayashi T, Akiba S, Kikuchi Y, *et al.* Mobile phone use and acoustic neuroma risk in Japan. Occup Environ Med 2006; 63(12): 802-7.
32. Schlehofer B, Schlaefer K, Blettner M, *et al.* Environmental risk factors for sporadic acoustic neuroma (Interphone Study Group, Germany). Eur J Cancer 2007; 43(11): 1741-7.
33. Klaeboe L, Blaasaas KG, Tynes T. Use of mobile phones in Norway and risk of intracranial tumours. Eur J Cancer Prev 2007; 16(2): 158-64.
34. The INTERPHONE Study Group. Brain tumour risk in relation to mobile telephone use: results of the INTERPHONE international case-control study. Int J Epidemiol 2010; 39(3): 675-94.
35. Lahkola A, Auvinen A, Raitanen J, *et al.* Mobile phone use and risk of glioma in 5 North European countries. Int J Cancer 2007; 120(8): 1769-75.
36. Myung SK, Ju W, McDonnell DD, *et al*. Mobile phone use and risk of tumors: a meta-analysis. J Clin Oncol 2009; 27(33): 5565-72.
37. Han YY, Kano H, Davis DL, *et al.* Cell phone use and acoustic neuroma: the need for standardized questionnaires and access to industry data. Surg Neurol 2009; 72(3): 216-22.
38. Huber R, Treyer V, Borbely AA, *et al.* Electromagnetic fields, such as those from mobile phones, alter regional cerebral blood flow and sleep and waking EEG. J Sleep Res 2002; 11(4): 289-95.
39. Krause CM, Sillanmaki L, Koivisto M, *et al.* Effects of electromagnetic fields emitted by cellular phones on the electroencephalogram during a visual working memory task. Int J Radiat Biol 2000; 76(12): 1659-67.
40. Benes FM, Turtle M, Khan Y, *et al.* Myelination of a key relay zone in the hippocampal formation

occurs in the human brain during childhood, adolescence, and adulthood. Arch Gen Psychiatry 1994; 51(6): 477-84.
41. Peyman A, Rezazadeh AA, Gabriel C. Changes in the dielectric properties of rat tissue as a function of age at microwave frequencies. Phys Med Biol 2001; 46(6): 1617-29.
42. Gandhi OP, Kang G. Some present problems and a proposed experimental phantom for SAR compliance testing of cellular telephones at 835 and 1900 MHz. Phys Med Biol 2002; 47(9): 1501-18.
43. De Salles AA, Bulla G, Rodriguez CE. Electromagnetic absorption in the head of adults and children due to mobile phone operation close to the head. Electromagn Biol Med 2006; 25(4): 349-60.
44. Fernández CR, Bulla G, Pedra AC, *et al.* Comparison of electromagnetic absorption characteristics in the head of adult and children for 1800 MHz mobile phones. Paper presented at: International Microwave and Optoelectronics Conference (IMOC 2005); Brasilia, Brazil, 2005.
45. Dimbylow PJ. Induced current densities from low-frequency magnetic fields in a 2 mm resolution, anatomically realistic model of the body. Phys Med Biol 1998; 43(2): 221-30.
46. ICRP. International Commission on Radiological Protection. Report of the task group on reference man. ICRP Publication 23. Oxford: Pergamon Press, 1992.
47. Gandhi OP, Lazzi G, Furse CM. Electromagnetic absorption in the human head and neck for mobile telephones at 835 and 1900 MHz. IEEE Trans Microw Theory Tech 1996; 44(10): 1884-97.
48. Kang G, Gandhi OP. SARs for pocket-mounted mobile telephones at 835 and 1900 MHz. Phys Med Biol 2002; 47(23): 4301-13.
49. Wang J, Fujiwara O. Comparison and evaluation of electromagnetic absorption characteristics in realistic human head models of adult and children for 900-MHz mobile telephones. IEEE Trans Microw Theory Tech 2003; 51(3): 966-71.
50. Gandhi OP, Kang H. Inaccuracies of a plastic “Pinna” SAM for SAR testing of cellular telephones against IEEE and ICNIRP safety guidelines. IEEE Trans Microw Theory Tech 2004; 52(8): 2004-12.
51. Martinez-Burdalo M, Martin A, Anguiano M, *et al.* Comparison of FDTD-calculated specific absorption rate in adults and children when using a mobile phone at 900 and 1800 MHz. Phys Med Biol 2004; 49(2): 345-54.
52. Wiart J, Hadjem A, Wong MF, *et al.* Analysis of RF exposure in the head tissues of children and adults. Phys Med Biol 2008; 53(13): 3681-95.
53. Kuster N, Gosselin MC, Kuhn S, *et al.* Past, current, and future research on the exposure of children. ITIS Foundation Internal Report 2009.
54. Schonborn F, Burkhardt M, Kuster N. Differences in energy absorption between heads of adults and children in the near field of sources. Health Phys 1998; 74(2): 160-8.
55. Anderson V. Comparisons of peak SAR levels in concentric sphere head models of children and adults for irradiation by a dipole at 900 MHz. Phys Med Biol 2003; 48(20): 3263-75.
56. IEEE. IEEE Std 1528™-IEEE recommended practice for determining the peak spatial-average Specific Absorption Rate (SAR) in the human head from wireless communications devices: measurement techniques. 2003.
57. IEEE. IEEE Std C95.3™-IEEE recommended practice for the measurement of potentially hazardous electromagnetic fields - RF and Microwave. 1991.
58. IEEE. IEEE Std C95.1™-IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz. 1999.
59. NRC. National Research Council- Identification of research needs relating to potential biological or adverse health effects of wireless communication, 2008.
60. Kuster N, Schuderer J, Christ A, *et al.* Guidance for exposure design of human studies addressing health risk evaluations of mobile phones. Bioelectromagnetics 2004; 25(7): 524-9.
61. Lai H. Biological effects of radiofrequency electromagnetic field. In: Bowlin GL, Wnek G, eds. Encyclopedia of Biomaterials and Biomedical Engineering. DOI: 10.1081/E-EBBE-120041846, 2005.
62. Tell RA, Mantiply ED. Population exposure to VHF and UHF broadcast radiation in the United States. Proceedings of the IEEE 1980; 68: 6-12.