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Absorption of wireless radiation in the child versus adult brain and eye from cell phone conversation or virtual reality

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ABSTRACT

Children's brains are more susceptible to hazardous exposures, and are thought to absorb higher doses of radiation from cell phones in some regions of the brain. Globally the numbers and applications of wireless devices are increasing rapidly, but since 1997 safety testing has relied on a large, homogenous, adult male head phantom to simulate exposures; the "Standard Anthropomorphic Mannequin" (SAM) is used to estimate only whether tissue temperature will be increased by more than 1 Celsius degree in the periphery. The present work employs anatomically based modeling currently used to set standards for surgical and medical devices, that incorporates heterogeneous characteristics of age and anatomy. Modeling of a cell phone held to the ear, or of virtual reality devices in front of the eyes, reveals that young eyes and brains absorb substantially higher local radiation doses than adults'. Age-specific simulations indicate the need to apply refined methods for regulatory compliance testing; and for public education regarding manufacturers' advice to keep phones off the body, and prudent use to limit exposures, particularly to protect the young.

1. Introduction

With many nations having more mobile phones than people, and the rapidly increasing use of wireless transmitting devices by infants, toddlers and young children, it is important to consider children's unique absorption of radiofrequency (RF), also called microwave (MW) non-ionizing radiation (Gandhi et al., 1996; de Salles et al., 2006; Wiart et al., 2008; Christ et al., 2010) and potential health impacts.

Standards for wireless devices have not changed since 1997, and are based on the assumption that the only adverse effect to be avoided is heat (Gandhi et al., 2012). Mobile phones are certified to be within RF radiation regulatory limits using robot-assisted determination of peak spatial Specific Absorption Rate (psSAR) – i.e. maximum dose rate – within a phantom of a large, adult male head and body, the Standard Anthropometric Mannequin (SAM). The plastic SAM head mold, filled with a homogeneous liquid to simulate dielectric characteristics of soft tissues at the frequency of the device being tested, is assumed to be valid for those with younger and smaller heads (U.S. Federal Communications Commission (FCC) Office of Engineering and Technology, 1997; IEEE International Committee on Electromagnetic Safety (SCC39), 2005), to test compliance with outdated standards set for exposure to the entire head. This ignores human anatomy, and the fact that the brain and eyes are target tissues where such radiation can be especially biologically important. Studies have consistently indicated that children's brains absorb substantially higher peak doses than adults (Morris et al., 2015; Foster and Chou, 2016).

Anatomically-based, age-appropriate mathematical models of younger heads with thinner skulls and higher water content were used to examine specifics of psSAR averaging volume and dielectric constants within specific regions of the head. Specific regions include the eye and brain, to aid interpretation of international standards (Institute of Electrical and Electronics Engineers, 2013; Gosselin et al., 2014; International Commission on Non-Ionizing Radiation Protection, 1998; Peyman et al., 2009). Age-appropriate simulations are used to advance the understanding of the exposure of critical parts of the brain to RF radiation using models over a broad range of ages (from 3 to 34 years) (Fernandez-Rodriguez et al., 2015) from cell phones used against the ear, as well as in front of the face to view virtual reality (Google, n.d.).

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2. Materials and methodology

2.1. Cell phone model

A dual band (900 MHz and 1800 MHz) model was used (Garzon et al., 2013), with a common cell phone case 109 × 60 × 13.9 mm and a Planar Inverted "F" Antenna (PIFA) in the top position. This antenna is widely used in modern phones. With the exception of virtual reality modeling, the phone was in the "touch" position (touching the cheek, with the antenna over the ear). Although manufacturers specify that wireless devices should be kept a minimum distance from the body in order to ensure meeting exposure standards, in this work the phone was modeled as it is commonly used, against the skin, with dimensions from phone to brain as indicated below. Virtual Reality (VR) modeling was carried out for a system similar to the Google Cardboard (Google, n.d.) in which the cell phone is positioned in front of the eyes. The distances between the antenna (inside the phone) and the eye lens are: 31.37 mm for Thel and 46.64 mm for Duke, based upon the dimensions of the anatomical models.

2.2. Head models

Head models of the 8 and 10 year old boys, developed by Porto Alegre/Environmental Health Trust (PAEHT) for this work, were obtained via segmentation of Computerized Tomography (CT) images of specific children after approval by the ethics committee of the Mae de Deus Hospital in the "Parecer n° 556/12 do Comité de Ética em Pesquisa do Hospital Mãe de Deus CEP/HMD," in Porto Alegre, Brazil. All other head models belong to the "Virtual Family" (VF) developed by the Swiss National Institute of Technology Research (IT'IS) in collaboration with the U.S. Food and Drug Administration. The VF, representing average dimensions and anatomy for the gender and age, have been detailed elsewhere (Gosselin et al., 2014). SAM, the homogenous head model employed by telecommunication testing worldwide is based on a male with a head weighing about 11 pounds, representing the 90th percentile of U.S. military recruits in 1989.

The models are: 3 year-old boy (Indy from VF; 13 mm distance antenna to brain (atb)), 5 year-old girl (Roberta from VF; 20 mm atb), 6 year-old boy (Thelonious from VF; 23 mm atb), 8 year-old girl (Eartha from VF; 29 mm atb), 8 year-old boy (David developed by PAEHT; 23 mm atb), 10 year-old boy (Diego developed by PAEHT; 24 mm atb), 11 year-old girl (Billie from VF; 26 mm atb), 14 year-old boy (Louis from VF; 19 mm atb), 26 year-old woman (Ella from VF; 29 mm atb), 34 year-old man (Duke from VF; 32 mm atb) and SAM (8 mm atb) (Institute of Electrical and Electronics Engineers, 2013). In the Diego, Duke, Louis and Thelonious simulated versions, the pinna has not been identified.

psSAR simulations were repeated in triplicate for a range of ages, grid sizes, and dielectric parameters, employing standard protocols as summarized below.

2.3. Dielectric parameters

Adult parameters obtained from the work of Gabriel (1996) are regularly used for this purpose in medical applications. Age specific parameters for children were estimated based on accepted methods by correlating age specific measurements in pigs (Peyman et al., 2009) with Gabriel data (Gabriel, 1996) and interpolating using the following equation:

$$P(a) = \left[\frac{P_{50} - P_{10}}{12 - 4} \times a + \left(P_{50} + \frac{P_{50} - P_{10}}{12 - 4} \times 12\right)\right] \times \left(\frac{P_H}{P_{250}}\right)$$

where,

P is one of the dielectric parameters (permittivity or conductivity) of a given tissue;

a is the age (in years) for which the parameters are being adjusted (a must be in the range 4–12 years);

P_{250}, P_{50} and P_{10} are the parameter values measured in pigs (Peyman et al., 2009) weighing 250 kg, 50 kg and 10 kg corresponding to human ages of 18 (and adults), 12 and 4 years respectively;

P_H, is the value of the parameter published in Gabriel (1996), which is widely accepted as "adult human parameters."

2.4. Simulations

Software – SEMCAD X 14.8. Hardware – aXware TESLA C1060@ Intel i5 – 3470 CPU 3.20 GHz, 32 GB RAM. Grid characteristics – voxel dimensions: from 0.002 to 0.07 wavelength (0.67–23.3 mm in surrounding space); grading and relaxation ratio: 1.2 minimum padding: 0.2 wavelength (6.67 cm of free space around the head); total model size: from 4 M to 54 M cells. Source characteristics – frequency: 900 MHz; power delivered: 250 mW; bandwidth: 200 MHz and harmonic (0 Hz); typical simulation length: 40 periods. Simulation time – from 30 min to 5 h depending on the grid adjustment (dimensions and orientation) and frequency bandwidth. Validation – Loss and radiated power > 240 mW (@ Pdel = 250 mW). Uncertainties were estimated by varying simulation parameters (e.g. refining the mesh) and measuring the power budget. All psSAR values are in W/kg.

3. Results

When cell phones are held close to the head most of the energy (more than 80%) from the transmitting antenna is absorbed by the head. When the phone is used for virtual reality viewing, the head absorbs 50% of the energy.

3.1. Averaging volumes

Different averaging volumes are used in RF radiation regulatory limits, with North American standards referencing a cube of tissue weighing 1 g (U.S. Federal Communications Commission (FCC) Office of Engineering and Technology, 1997), while the International Commission on Non-Ionizing Radiation Protection (ICNIRP) relies on a 10 g volume ("Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). (International Commission on Non-Ionizing Radiation Protection", 1998). psSAR in the whole head (ear and/or skull) as well as in the brain varies inversely with averaging volume (Fig. 1), as smaller volumes are on average closer to the antenna. Another consequence is that the SAM head psSAR values are higher than values calculated using anatomical models, by approximately 1.7-fold in 10 g of tissue and 1.4-fold in 1 g of tissue. Several factors contribute to this trend: the SAM head model has no skull so psSAR is measured in simulation fluid that mimics soft tissues (bone absorbs RF radiation less avidly than the brain); the SAM head has a non-absorbing space simulating a compressed 6 mm thick pinna, while the anatomical models have uncompressed pinnas ranging from 5 mm in Indy to approximately 2 cm in Duke, and these outer ears do absorb radiation; and the relatively large head model of SAM presents a flatter surface adjacent to the antenna, compared with the smaller, rounded heads of the anatomical models.

Consistent with previous reports (Kang and Gandhi, 2002), the averaging volume employed in the modeling is correlated inversely with the calculated maximum tissue dose or psSAR (Fig. 1). Averaging the SAR over 10 g of tissue with a 2 W/kg maximum SAR (consistent with the ICNIRP recommendation) permits over 3-fold greater radiation absorption in the skull ("head" per regulatory standards), compared with averaging over 1 g of tissue with a 1.6 W/kg maximum SAR (consistent with current FCC/FDA methods). Furthermore, averaging SAR over 0.1 g – one-tenth the smallest mass in current use – yields a tissue dose up to 6 times that calculated for the commonly used 10 g mass standard.

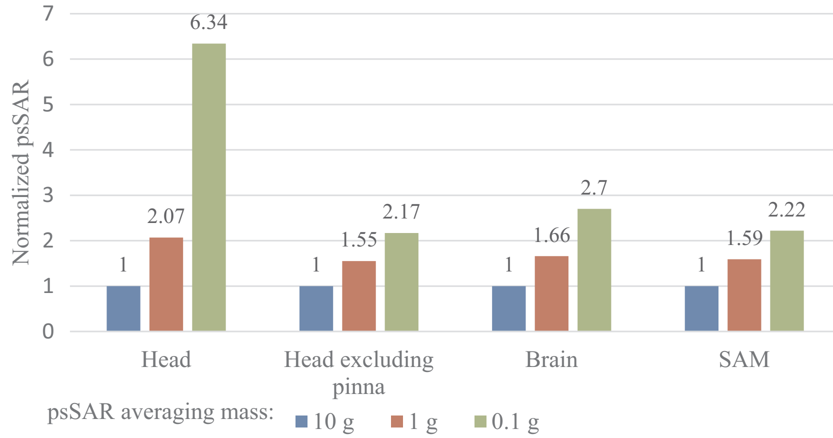

Fig. 1. psSAR averaged over cubic volumes containing 1 g and 0.1 g, relative to 10 g of continuous tissue. Values are normalized to the 10 g psSAR. Head including and excluding pinna, and brain psSAR values are averages of the psSAR obtained for 10 anatomical models. SAM is also presented.

The remainder of this report presents SAR data within 1 g cubes.

3.2. Developmental trends and tissue-specific doses

The psSAR for the skull, as predicted by these models, rises through childhood as the skull thickens, and then falls from youth to adulthood as the proportion of marrow in the bone decreases. The psSAR in the brain decreases with increasing age, with brain in the youngest models absorbing approximately 2-fold to 3-fold higher doses of RF radiation than older female and male models respectively.

Tissues that have been shown to absorb 80% of the radiation from a cell phone placed next to the head (Cardis et al., 2008) may be particularly sensitive and vulnerable to effects of RF radiation. These include the cerebellum, temporal and frontal lobes, and cheek (including parotid gland) and eyes. With the phone against the ear, the psSAR in the hippocampus and the cerebellum (Fig. 2) is greater in the younger models, with approximately 2-fold greater psSAR in the cerebellum, and approximately 30-fold greater psSAR in the hippocampus.

It is undisputed that the eyes are particularly vulnerable to RF radiation, as a result of little fluid circulation and thus poor cooling, plus high RF radiation absorption as a result of relatively high water content. The eyes in the youngest models absorb between 2-fold and almost 5-fold higher doses of RF radiation than those of the older models (Fig. 2). Older males' heavier features offer particular protection to the eyes when the phone is used for conversation.

Model geometry as well as dielectric constants change systematically with age, with greater head mass, and skull and skin thickness in adults compared with children. Fig. 3, psSAR in the grey matter as a function of distance from the antenna (approximating the pinna plus skull), depicts a clear trend of decreasing psSAR with increasing distance (as expected) and illustrates the trend amongst models. Substantial inter-individual variation in psSAR is seen in the more than two-fold difference between the David and Eartha models, both 8 years of age.

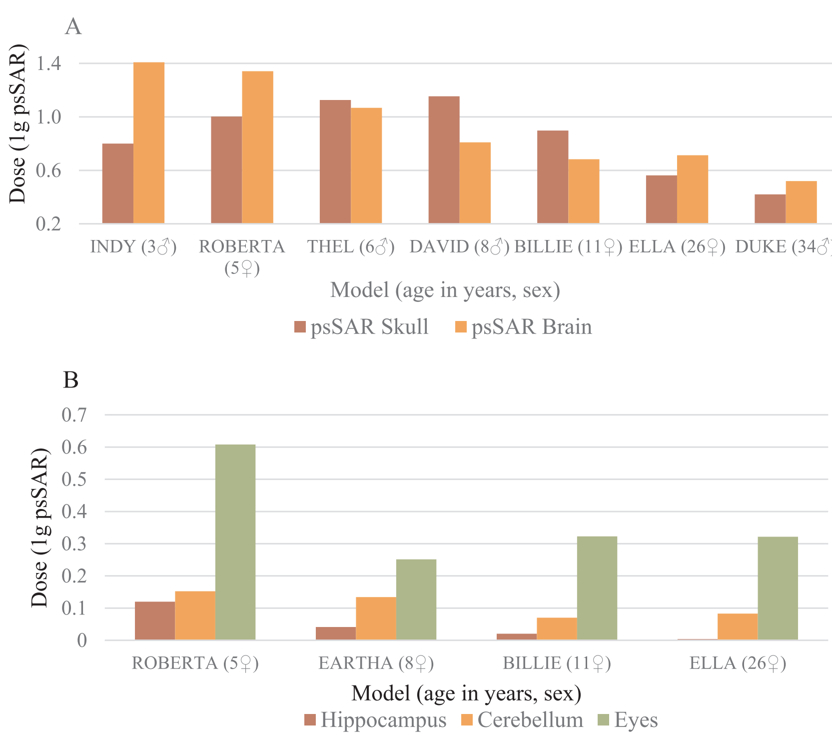

Fig. 2. psSAR in 1 g of specific tissues. A. the skull and brain and B. specific tissues in models with these features identified – hippocampus, cerebellum and eyes.

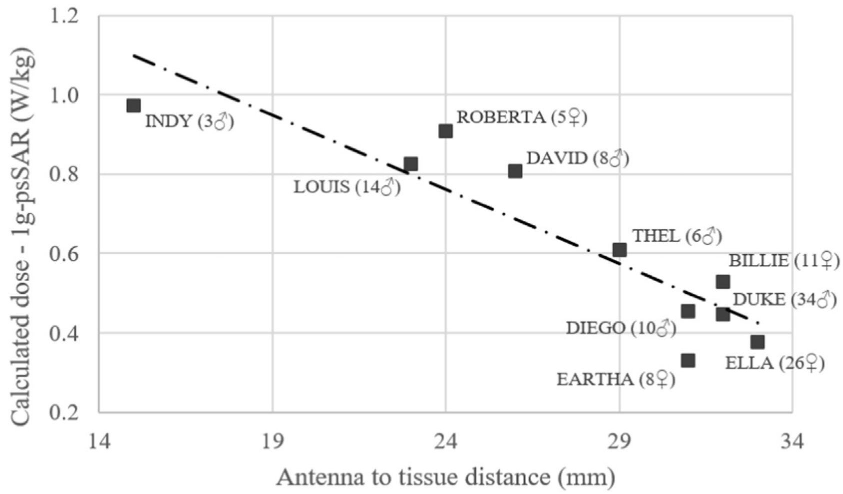

Fig. 3. Trend of psSAR in 1 g of grey matter, as a function of distance from the antenna to the brain, for phone in "talk" position.

3.3. Visualization of child versus adult doses

The previously quantified differences between doses of RF radiation (SAR) in critical components of the brain of the child and adult are clearly illustrated in Fig. 4, in child (Thelonious) and adult (Duke) head models, when the phone is used for talking, or for viewing virtual reality. The eyes and frontal lobe of the 6 year old model experiences a roughly 3-fold higher SAR than the adult's when a virtual reality cardboard holder containing a phone is placed directly in front of the eyes (Fig. 4B).

4. Discussion

In summary, compared with adult models, children experience two- to three-fold higher RF doses to: 1) localized areas of the brain when a cell phone is positioned next to the ear; and 2) the eyes and frontal lobe when a cell phone is used to view virtual reality. These findings raise serious questions about the current approach to certify cell phones; particularly the use of the SAM.

In 2012, the U.S. Government Accountability Office advised that the test system used to estimate human exposure should be modified to reflect changing uses and users of mobile phones (US Government Accountability Office, 2012). The analyses presented here further support the need for more pertinent modeling, particularly in light of the growing use of phones and other wireless transmitting devices by infants, toddlers and young children, and new modes of use such as virtual reality. The current SAM Certification Process should be replaced, or at least complemented with computer simulation such as FDTD, as currently approved by the FDA and FCC. Certification should include child models, and should be based on a 1 g or lower averaging mass.

The influence of the averaging mass is important when comparing radiation standards for North America with an averaging mass of 1 g versus international standards based on 10 g of tissue, as psSAR values are lower within greater averaging masses. The differences in psSAR measured above are a mathematical consequence of the fact that the center of gravity of a larger tissue cube is further from the source. SAM is a homogenous model, but in order to discern risks for specific regions and small structures (e.g. parotid gland, or acoustic nerve that are suspected as being affected by RFR), it is necessary to model a physiologically relevant volume. Besides, 0.1 g of human tissue may contain 55 million cells (glial cells and neurons) (von Barthel et al., 2016; Garman, 2011; Herculano-Houzel and Kaas, 2011); moreover, the initiation of cancer is commonly thought to originate with the mutation of as few as one cell, for example as evidenced by clonal consistency in early stages of pediatric glioma (St. Jude Children's Research Hospital, 2012; Alcantara Llaguno and Parada, 2016).

In 2011, IARC classified RF/MW radiation as a possible human carcinogen (group 2B) (Baan et al., 2011), and subsequent epidemiological findings strengthen this finding (Hardell and Carlberg, 2015). In

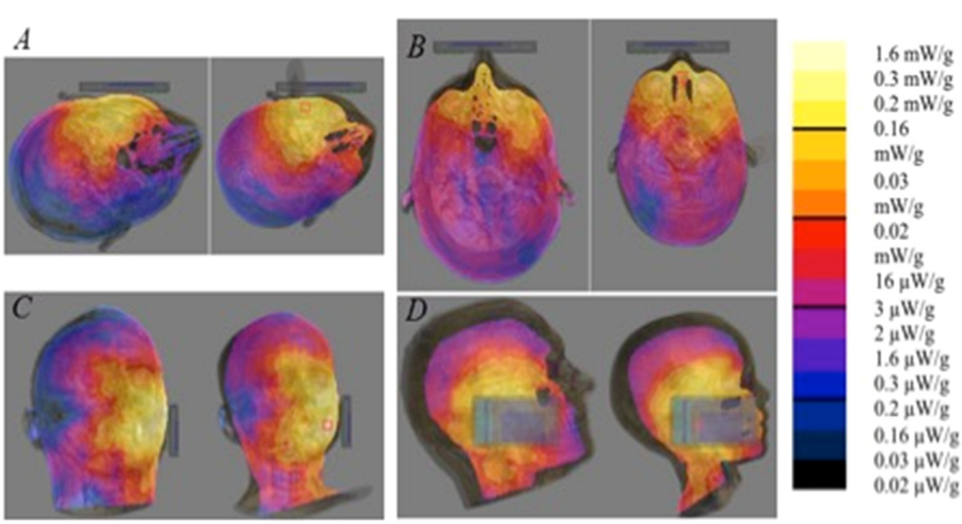

Fig. 4. SAR in cross-sectional views of child and adult male heads, with phone in talk and in virtual reality positions. A Axial slices (top view) of Thelonious (6 y) and Duke (34 y), with cell phone in cheek position, intersecting the eyes; B Axial slices (top view) of Thelonious (6 y) and Duke (34 y), with cell phone in virtual reality position, intersecting the eyes; C Quasi-coronal slices (frontal view) of Thelonious (6 y) and Duke (34 y) with cell phone in the cheek position, through the ear; D Parasagittal slices (side view) of Thelonious (6 y) and Duke (34 y), with cell phone in virtual reality position, intersecting the eye. The scale is 50 dB with 0 dB = 1.6 mW/g.

2016 the first results of U.S. National Toxicology Program animal studies reported that non-thermal levels of both GSM and CDMA wireless radiation – irregularly pulsed signals – significantly increased highly malignant rare cancers of the brain and heart (Wyde et al., 2016). Independent analysts find that these scientific advances merit IARC reclassification to 2A or even 1 ("known human carcinogen").

Our modeling demonstrates clearly that localized psSAR varies significantly for critical components of the brain. Younger models absorb proportionally more radiation in the eyes and brain – grey matter, cerebellum and hippocampus—and the local dose rate varies inversely with age. This reflects the fact that the head is not homogeneous. Indeed, localized heating up to 5 Centigrade degrees has been detected as a result of mobile phone radiation studied *ex vivo* in cow brain using Nuclear Magnetic Resonance thermometry (Gultekin and Moeller, 2013).

Not only do children absorb higher peak doses in the brain than adults, their brain is growing rapidly, subject to different windows of vulnerability, and thus more susceptible to insult. In particular, glial cells are in an early developmental stage in the newborn brain and develop, grow, and reproduce extensively throughout the brain during childhood and early adulthood. It appears that RF radiation induces cancer in these cells (Wyde et al., 2016).

Myelin, the protective fatty sheath around neurons, is thin in the young brain and develops through the mid-twenties (Redmayne and Johansson, 2014). Lower myelin levels and consequent higher water levels are responsible for greater absorption of RF energy in young brains. Myelin also provides some protection of neurons from RF and other potential neurotoxins.

Timing, type, duration and variability of toxicant exposure levels all modulate toxicity. Indeed, exposures that take place during fetal development or early childhood may cause permanent brain injury, whereas the same doses may have little or no impact in adults (Heindel et al., 2015). Analogously, a number of chemicals are known to exert differentially greater toxicity to the young brain and body. As well, peak exposures are far more important than averages, and early exposures more damaging as they affect a child's trajectory through life. For example, sudden shifts in benzene exposure are known to be more damaging than would be expected from average continuous exposures (Agency for Toxic Substances and Disease Registry (ATSDR), 2007). Lead exposures that occur prior to age two have greater impacts on the adult brain and body than those that occur later in life.

Early RF radiation exposures have also demonstrated long term effects. Experimental prenatal (Bas et al., 2009) and adolescent rodent (Kerimoğlu et al., 2016) exposures to mobile phone radiation have been shown to impair the development of the dentate gyrus and pyramidal cells and to affect behavior (Aldad et al., 2012; Saikhedkar et al., 2014), similar to how early life stressors also impair subsequent neurogenesis of the hippocampus, and learning (Narayanan et al., 2015; Huang, 2014; Musaelyan et al., 2014; Deniz et al., 2017). As the hippocampus plays a critical role in the development of memory, impulse control and a number of other critical cognitive and motor functions, greater RF radiation doses to this part of the young brain merits serious attention in revising standards for emissions from cell phones.

Interest in physiologically relevant modeling will likely intensify as effects of RF radiation beyond heating gain relevance in standards setting. A sweeping review of scientific omissions and misrepresentations, as well as conflicts of interests, in a recent UK review of RF exposure guidance clearly makes the case for much more restrictive, better-informed science-based standards (Starkey, 2016).

5. Conclusions

Our findings support reexamination of methods to determine regulatory compliance for wireless devices, and highlight the importance of precautionary advice such as that of American Academy of Pediatrics (2016). The Academy recommends that younger children should not use cell phones, and that prudent measures should be taken to eliminate exposure (e.g. using devices for amusement or education only when all wireless features are turned off – in "airplane mode") or to minimize exposure (e.g. texting or using speakerphone), and that cell phones should not be kept next to the body. Use of wires/cables in schools and homes circumvents needless exposures of children to radiation from both devices and Wi-Fi routers. There is also an urgent need for research to evaluate the risks to the eye from use of cell phones in virtual reality applications.

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Contributions

C. Fernandez: Conceptualization, Methodology, Investigation, Validation, Formal Analysis, Writing – Review & Editing

A.A. deSalles: Conceptualization, Project Administration, Supervision, Formal Analysis, Writing – Review & Editing

M.E. Sears: Conceptualization, Visualization, Writing – Original Draft Preparation & Editing

R.D. Morris: Conceptualization, Visualization, Writing – Review & Editing

D.L. Davis: Conceptualization, Funding Acquisition, Methodology, Project Administration, Supervision, Visualization, Writing – Review & Editing

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