Review and Analysis of Wi-Fi Devices and Radiofrequency Radiation in Schools for the Maryland Children's Environmental Health and Protection Advisory Council

Linda Li
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Maryland Institute for Applied Environmental Health
Committee: Dr. Paul Turner (Advisor), Dr. Lesliam Quirós-Alcalá, Dr. Devon Payne-Sturges

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Abstract

With growing concern over the potential adverse health effects of chronic exposure to Wi-Fi radiation, the Maryland Children's Environmental Health and Protection Advisory Council (CEHPAC) has formed a Workgroup to examine the issue of Wi-Fi routers and their use in K-12 schools in the state. This review serves as an overview of the state of the science available to date on Wi-Fi effects on biological outcomes, as well as exposure assessments of radiofrequency radiation in the general, non-occupational population. This literature search and review yielded mixed results and studies of varying quality. Exposure assessments found that typical and worst case scenario exposures are well below US and international guidelines for radiofrequency exposure. However, decades-old standards need updating in light of new science. This review will contribute to a larger report from CEHPAC in which recommendations will be made to aid policymakers and school administrators regarding the best way to approach Wi-Fi exposure in schools.

Introduction

In the past twenty years, Wi-Fi use has become near ubiquitous in homes, workplaces, public spaces, and increasingly, schools. "Wi-Fi" is defined by the Wi-Fi Alliance as any certified product using wireless local area network (WLAN) within IEEE 802.11 standards (Wi-Fi Alliance, 2016). Wi-Fi, therefore, applies to any product that can support WLANs, including mobile phones, laptops, tablet computers, and video game consoles, among others. With the widespread adoption of wireless technology in almost every aspect of modern life comes increasing concern for the potential negative health effects of constant exposure to radiofrequency electromagnetic radiation (RF-EMR) from electronic devices utilizing Wi-Fi technology. As more schools across the country become Wi-Fi equipped, advancing past traditional "hardwired" Ethernet internet connections, parents and other concerned parties are advocating for increased research into the potential adverse effects that could result from RF-EMR in environments where children spend a significant portion of their day. In fact, the concern is so strong that some parents and experts recommend that schools eschew Wi-Fi altogether and stay hard-wired, citing the precautionary principle (Sage & Carpenter, 2009).

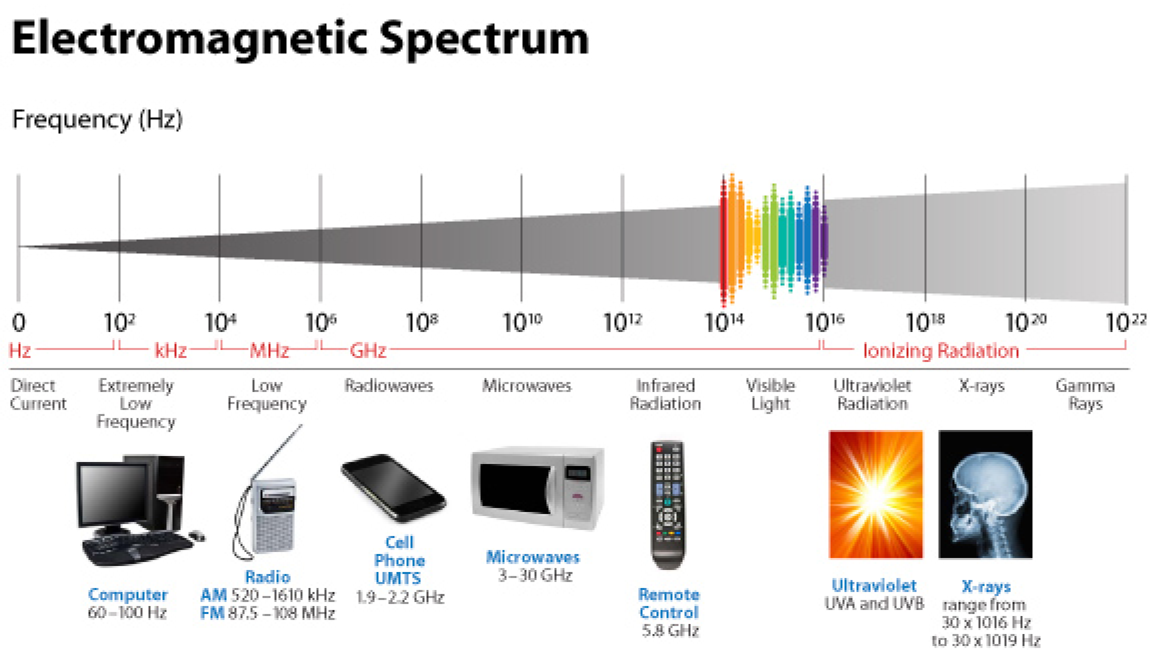
In Maryland, the Children's Environmental Health and Protection Advisory Council (CEHPAC) has formed a Wi-Fi Workgroup to investigate the issue of Wi-Fi in schools in the state. CEHPAC was created in 2000 when the Maryland General Assembly passed HB313 to establish a council to advise the Governor and General Assembly on environmental issues that may pose a threat to children. The Council is composed of members from Maryland state agencies such as the Department of Health and Mental Hygiene, the Department of Environment, and the Department of Education, as well as health care providers and partners from non-profit agencies and academic institutions (Maryland State Archives, 2016). The Wi-Fi Workgroup, comprised of scientists and environmental health experts, was specifically formed with the intention of reviewing the potential adverse effects of RF-EMR from Wi-Fi routers and to make recommendations in response to the urging of concerned parents in Maryland, particularly those with children in the Montgomery County Public School System.

This review seeks to examine the current state of the science regarding RF-EMR emitted by Wi-Fi devices. While there have been decades of research into RF-EMR, only recently has the focus turned to Wi-Fi. To date, the vast majority of the existing body of research on microwave radiation in the general population examines RF-EMR from mobile phones, which operate at different frequency bands than Wi-Fi devices. Usage of mobile phones also differs from that of Wi-Fi in that phones are typically held up to specific parts of the body (e.g. the face/ears, or the legs when the phone is in a pants pocket) and thus exposure to radiation from mobile phones is highly localized. This review will cover scientific research as it relates to exposure, dose, and potential adverse effects as a result of exposure to Wi-Fi. The results of this review will contribute to CEHPAC’s larger goal of determining whether any action should be taken with regard to Wi-Fi in Maryland schools. This review will later become part of a larger report from the Workgroup that will provide guidance to state legislators and other policymakers.

Background

Certified Wi-Fi devices in the United States operate in the 2.45 GHz and 5 GHz frequency bands, both of which fall under the spectrum of radiofrequency microwave radiation (Institute of Electrical and Electronics Engineers, 2013). Microwaves, which cover electromagnetic radiation frequencies between 300 MHz and 300 GHz, are considered non-ionizing radiation (See Figure 1). Compared to ionizing radiation, non-ionizing radiation does not have enough energy to ionize atoms and molecules, a process that leads to tissue and DNA damage (US EPA, 2015). Because of this, non-ionizing radiation has, up until recently, generally been considered safe at the levels emitted by electronic devices. Although non-ionizing radiation does not have enough energy to damage cells and DNA, it can cause atoms to vibrate, which produces thermal effects at high levels (US EPA, 2006).

Figure 1. The electromagnetic spectrum. Source: NIEHS (National Institute of Environmental Health Sciences, 2016)



While the thermal effects of high levels of exposure to microwaves are well-documented, there is increasing concern in regards to non-thermal effects of microwaves in the case of lower, chronic exposure (Pall, 2015). In 2011, the International Agency for Research on Cancer (IARC) classified RF-EMR, which includes microwaves, as Class 2B or "possibly carcinogenic" (Baan et al., 2011). The decision to classify RF-EMR as possibly carcinogenic was largely based on a handful of epidemiological studies that provide evidence for a possible association between mobile phone use and glioma (Auvinen, Hietanen, Luukkonen, & Koskela, 2002; Hardell, Carlberg, & Hansson Mild, 2011; Inskip et al., 2001; Muscat JE, Malkin MG, Thompson S, et al, 2000; Schüz et al., 2006; The INTERPHONE Study Group, 2010). Although the IARC review and report do not specifically mention Wi-Fi devices and RF-EMR in the Wi-Fi frequency bands, many are wary that the same health effects demonstrated through long-term mobile phone use may also occur from lifelong exposure to Wi-Fi radiation.

Currently in the US, wireless devices, including routers, are subject to regulation under the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards (Institute of Electrical and Electronics Engineers, 2013) as well as the Federal Communication Commission (FCC). All wireless devices sold in the US must not exceed the maximum allowable specific absorption rate (SAR) level when operating at the device's highest possible power level. The SAR is a value that corresponds to the rate at which RF energy is absorbed by body tissue. This limit, set in 1996, is 1.6 watts per kilogram (W/kg), averaged over one gram of tissue (Federal Communication Commission, 1997). Additionally, the International Commission on Nonionizing Radiation Protection (ICNIRP) published SAR guidelines for whole-body and local exposure in 1998. These limits are 0.08 W/kg and 2.0 W/kg, respectively (International Commission on Non-Ionizing Radiation Protection, 1998). These standards and guidelines are based on documented thermal effects of microwaves.

Methods

Literature Search

Literature searches were completed using PubMed/MEDLINE using the following search terms in late December 2015 to early January 2016:

wlan[All Fields] AND ("health"[MeSH Terms] OR "health"[All Fields])
wlan[All Fields] AND exposure[All Fields]
wifi[All Fields] AND exposure[All Fields]
wifi[All Fields] AND ("health"[MeSH Terms] OR "health"[All Fields])
wi-fi[All Fields] AND ("health"[MeSH Terms] OR "health"[All Fields])
wi-fi[All Fields] AND exposure[All Fields]

This search strategy yielded a total of 260 articles that were then vetted for relevance. Searches were completed primarily on the University of Maryland (UMD), College Park campus. For additional resources such as access to medical science databases not available in College Park, some articles were retrieved at the UMD, Baltimore Health Sciences and Human Services

Library. After database search, additional articles for review were identified through e-mail correspondence with experts. During the course of this literature search, CEHPAC received e-mails from scientists and physicians calling for hardwired schools in Maryland, many of which cited peer-reviewed articles and other materials related to the issue of Wi-Fi in schools. This yielded 25 additional records for review.

Exclusion Criteria

The literature review process was based on the PRISMA Statement guide for reporting systematic reviews and meta-analyses (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). From the database search, 260 articles were identified, 92 of which were kept after an initial screening based on title and abstract. Due to the timeline and scope of this report, only studies conducted using Wi-Fi frequencies, i.e. 2.45 GHz or 5 GHz, were considered. Articles related to cell phones, cordless landline phones, and other sources of microwave radiation besides WLAN access points/routers and antenna were excluded. Articles focusing on Wi-Fi radiation from cell phones were also excluded as they did not contribute to the main research question regarding routers in schools. After 34 duplicates were removed, 58 articles remained for full-text review. Of the 25 records from the e-mails, 12 were duplicates of articles identified from the database search, leaving 13 records for review. In total, 71 records advanced to full-text assessment and review.

The remaining 71 records from e-mails and database searches were assessed for eligibility for inclusion in the final literature review. Ten articles were excluded because they were methods papers written with the intention of informing the design of future studies in exposure assessment and/or measuring potential biological effects of microwave radiation at Wi-Fi frequencies. These articles are highly technical and do not contribute results that would be useful for this literature review. Three articles were excluded because they did not measure exposure or effects specifically of Wi-Fi from routers, but rather radiation from cell phones and other sources. Two articles were reviews of EMF-related health concerns that had no specific focus on Wi-Fi. Two records were excluded because they were not scientific studies of EMF exposure; one was an exposé of the electronics industry and one was a signed letter. Seven records were excluded because they did not specifically address the issue of Wi-Fi exposure, but instead proposed biological mechanisms for non-thermal effects of all RF-EMF.

The 47 studies included in this report were reviewed for article type (*in vitro, in vivo,* exposure assessment, etc.; see “Results of Literature Review”), study population, methods and/or study design, exposure system when applicable, main results, and strengths and limitations.

Results of Literature Review

Exposure assessment

The majority of surveys of RF-EMR exposure have taken place in Europe in a variety of indoor and outdoor environments. While every study in this review included Wi-Fi frequencies in their exposure assessments, most studies measured all sources of RF radiation to ascertain the relative contributions of each source. Many exposure studies used the ICNIRP reference level for electric field strength exposure for the general public, currently set at 61 V/m for devices in the 2-300 GHz range (International Commission on Non-Ionizing Radiation Protection, 1998). This is different from the ICNIRP reference level SAR because electric field strength does not measure absorbed RF-EMR, but instead describes the strength of radiation from devices in a given area. Urbinello et al. performed measurements in Basel, Ghent, and Brussels in Belgium with portable RF exposure meters in outdoor residential and urban areas, inside public transportation, and in indoor spaces such as airports, shopping malls, and railway stations (Urbinello, Joseph, Verloock, Martens, & Röösli, 2014). The highest measured exposure occurred in public transport, with means of 0.84 V/m in Brussels, 0.72 V/m in Ghent, and 0.59 V/m in Basel. All exposure levels obtained in the study were below ICNIRP guidelines. This study measured 11 frequency bands, ranging from Wi-Fi to FM radio and mobile phones. Therefore, the exposure levels obtained by the researchers are an indication of total exposure from all RF-EMR, not just Wi-Fi itself. However, the authors did note that mobile phones were the main source of exposure inside trains, and that base stations contributed most of the radiation in outdoor settings. In indoor settings, both sources had considerable contributions.

Verloock and colleagues completed several other exposure assessments in Belgium. Looking at Wi-Fi frequencies only, the researchers characterized WLAN exposure in 222 office location scenarios and in a wireless sensor lab environment (WiLab) (Verloock, Joseph, Vermeeren, & Martens, 2010). Average exposure to WLAN in an office environment with WiLab off was 0.12 V/m with a 95th percentile measurement of 0.90 V/m. With WiLab on, exposure increased to 1.9 V/m with a 95th percentile of 4.7 V/m. Results from the study were all below the ICNIRP guidelines of 61 V/m for distances of more than one meter from the Wi-Fi access point. It should also be noted that the intensity of radiation from wireless devices falls of rapidly with increasing distance from the source of energy, in what is known as the inverse-square law (Foster & Moulder, 2013). Another study by the same group characterized RF-EMR in schools, homes, and public places – three microenvironments where children are likely to be present. Average and maximal total RF-EMR values in schools, homes, and public places were 0.2 and 3.2 V/m, 0.1 and 1.1 V/m, and 0.6 and 2.4 V/m respectively, all of which are lower than ICNIRP limits (Verloock et al., 2014). In schools, the highest exposures came from Wi-Fi, while telecommunication signals such as those from mobile phones were highest at home and in public places. Joseph et al. found that 95th percentiles of field values due to Wi-Fi ranged between 0.36 and 0.58 V/m in indoor and office environments (W. Joseph, Vermeeren, Verloock, Heredia, & Martens, 2008).

Viel et al. supplied participants with personal exposure meters deployed for 24 hours in the rural/suburban region of Besançon and the urban area of Lyon (Viel, Cardis, Moissonnier, de Seze, & Hours, 2009). The meters measured RF-EMR in 12 different bands, and participants also kept a time-location-activity diary. Though the majority of recorded field strengths were below detection level, the highest mean exposure resulted from FM sources (0.044 V/m), followed by WiFi-microwaves (0.038 V/m), cordless phones (0.037 V/m), and mobile phones (UMTS: 0.036 V/m, UMTS: 0.037 V/m). Exposure was highest in urban areas during daytime. Bolte and Eikelboom conducted 24 hour personal exposure measurements in 12 frequency bands in Amsterdam and Purmerend in The Netherlands (Bolte & Eikelboom, 2012). Mean total exposure was 0.277 V/m with 37.5% of power density from mobile phones, 31.7% from cordless phones, 14.1% from Wi-Fi, 12.7% from base stations, and 3% from FM. In a study by Valič et al., children under the age of 17 wore personal exposure meters living in an apartment above a transformer substation and found exposure to RF-EMR to be under ICNIRP guidelines (Valič, Kos, & Gajšek, 2015).

Several other studies investigated scenarios of typical personal exposure at home, work, and public spaces. Vermeeren et al. measured exposure in 55 indoor microenvironments in Belgium and Greece (Vermeeren et al., 2013). The highest cumulative field values found were 3.6 V/m and 2.1 V/m in Belgium and Greece, respectively, both of which fall within ICNIRP guidelines. Dominating signals in almost every setting were GSM900 and GSM1800, both of which come from mobile phones. Schmid et al. measured RF-EMR from wireless communication devices such as WLAN, Bluetooth, cordless phones, and baby monitors in indoor environments, and found all devices fall under ICNIRP guidelines as well (Schmid, Lager, Preiner, Uberbacher, & Cecil, 2007). Lahham et al. examined RF-EMR exposure in Hebron, West Bank and found contributions to exposure were 46% from FM radio, 26% from mobile phones, 15% from cordless phones, 9% from WLAN, 3% from unknown sources, and 1% from TV broadcasting (Lahham, Sharabati, & ALMasri, 2015). Power densities measured in this study were also below ICNIRP guidelines. Tomitsch and Dechant examined temporal trends in household RF-EMR in Austria between 2006 to 2012 and found the highest increases in exposure from mobile communications and WLAN frequencies, with higher overall RF-EMR in urban areas (Tomitsch & Dechant, 2015).

Four exposure studies from this literature search focused exclusively on RF-EMR from Wi-Fi. Foster measured RF-EMR from WLANs in the US, Germany, France, and Sweden in private residences and public spaces (Foster, 2007). Measurements in public spaces were conducted as close as possible to access points and additional measurements were made one meter from an internet-connected laptop to simulate bystander exposure. All measurements were below ICNIRP exposure limits. Peyman et al. measured power densities of Wi-Fi devices in UK schools (Peyman et al., 2011). The maximum electric field strength recorded from the laptops and access points in this study at 0.5 m was 5.716 V/m which corresponds to a maximum power density value of 87 mW/m^2 (0.087 W/m^2), well below the ICNIRP reference value of 10 W/m^2.

Khalid et al. examined duty factors of laptops and access points in primary and secondary schools in the UK (Khalid et al., 2011). Duty factor refers to the fraction of time in which the Wi-Fi device is transmitting signal. This is an important aspect to consider in exposure assessments because Wi-Fi devices emit intermittent bursts of RF energy that differ over time. Duty factors in the laptops ranged from 0.02 to 0.91%, with a mean of 0.08%. Duty factors were higher in access points, which ranged from 1.0% to 11.7% with a mean of 4.79%. Applied to a model of a 10 year old child, the approximate SAR would be 80 μW/kg with a power density of 220 $\mu W/m^2$ at 0.5 m away from the laptop. Khalid then goes further and extrapolates the exposure to a classroom of 30 laptops, where personal exposure in the classroom could reach 16.6 mW/m^2 (0.0166 W/m^2), which falls under the ICNIRP reference level of 10 W/m^2. Findlay and Dimbylow also calculated SARs from a sitting 10 year old child voxel, or 3D graphical model, using Wi-Fi frequencies at 2.45 GHz and 5 GHz (Findlay & Dimbylow, 2010). In this study, a “typical” exposure scenario was an antenna operating at 100 mW, a duty factor of 0.1, and an antenna-body separation of 34 cm. This resulted in a peak localized SAR of 3.99 mW/kg

(0.00399 W/kg) in the torso. With a high duty factor of 1, the SAR was 5.7 mW/kg (0.0057 W/kg). Both of these estimates fall below ICNIRP guideline SARs.

Human phantom models, including voxel models, are often used by scientists in the field of health physics to conduct ionizing radiation dosimetry studies. The phantoms are computer-generated graphical representations of human physiology that allow for modeled exposure. Joseph et al. used human phantom models to derive SAR values following the collection of field measurements (Wout Joseph, Vermeeren, Verloock, & Martens, 2010). A typical scenario in which a person is exposed to multiple sources of RF-EMR, including Wi-Fi, yields an SAR below the ICNIRP recommended level. However, it is important to note that the authors found the highest estimated SAR values for the 1-year old child, followed by the 5-year old, the 10-year old, and then the average woman and man. Martínez-Búrdalo et al. calculated the SAR in a model of a human head and torso exposed to Wi-Fi and a Bluetooth signal at the same time (Martínez-Búrdalo, Martín, Sanchis, & Villar, 2009). Results of this study were also below ICNIRP limits even when set at worst-case scenario exposure levels. A summary of the exposure assessments discussed is seen in Table 3.

In vitro studies

In vitro studies have primarily focused on human sperm cells and the potential effects of Wi-Fi on fertility. Avendaño et al. exposed motile sperm to an internet-connected laptop for four hours and compared the results to an aliquot of unexposed sperm sample (Avendaño, Mata, Sanchez Sarmiento, & Doncel, 2012). Exposed sperm were placed 3 cm away from the laptop to simulate a scenario in which a man holds a laptop in his lap. While there was no significant difference in dead sperm count between the exposed and unexposed samples, there was significant decrease in sperm progressive motility and a higher proportion of sperm with DNA fragmentation in exposed sperm. Oni et al. also exposed sperm to 2.4 GHz Wi-Fi from a connected laptop for one hour, but kept the samples 60 cm away from the laptop antenna (Oni, Amuda, & Gilbert, 2011). The researchers found significant effects of Wi-Fi exposure on sperm concentration, motility and morphology grading of the sperm. Yildirim et al. did not conduct an experiment with sperm samples and Wi-Fi exposure, but collected samples from men who then completed a questionnaire for information on mobile phone and Wi-Fi use (Yildirim et al., 2015). There was a negative correlation between wireless internet usage and sperm count, with total and progressive motile sperm count decreasing with increased internet usage.

Other than *in vitro* studies of sperm, one study was conducted that assessed the effect of RF-EMR in breast cancer cells. Çiğ and Nazıroğlu had three exposure groups at 900 MHz and 1800 MHz mobile phone radiation, and 2.45 GHz Wi-Fi signals, which were further divided by 0 cm, 1 cm, 5 cm, 10 cm, 20 cm, and 25 cm exposure distance (Çiğ & Nazıroğlu, 2015). Researchers examined calcium signaling, cytosolic reactive oxygen species production, cell viability, apoptosis, and caspase-3 and -9 in response to exposure at the three frequency bands. Exposure within 10 cm of the cells induced excessive oxidative responses and apoptosis. These effects would indicate heat and oxidative stress as a result of RF exposure. However, no significant effects were found at 20 cm and 25 cm distances when compared to the control group, indicating protection from RF-EMR with increased distance from the source. A summary of *in vitro* studies is seen in Table 2.

In vivo studies: animal

Animal studies of Wi-Fi exposure have yielded mixed results. Studies have been conducted to test a variety of hypothesized effects, including reproductive function, oxidative stress, cognitive impairment, pregnancy and prenatal development, and immune system development.

Shahin et al. investigated the long-term effects of low-level 2.45 GHz microwave exposure on the reproductive function of male Swiss strain mice (Shahin, Mishra, Singh, & Chaturvedi, 2014). Mice were exposed for two hours a day for 30 days at an average SAR of 0.018 W/Kg, after which sperm count and sperm viability tests were conducted and vital organs were collected and processed for other analyses. Compared to unexposed mice, the researchers found a significant reduction in sperm count and viability, as well as reduction in testicular 3β HSD activity and plasma testosterone levels and an increase in nitric oxide synthase in the exposed group. These results indicate chronic exposure to microwaves could potentially lead to infertility through a free radical species-mediated pathway (Shahin et al., 2014). Shokri et al. found similar decreases in sperm parameters in male Wistar rats exposed to 2.45 GHz microwaves for one hour a day for two months and seven hours a day for two months (Shokri, Soltani, Kazemi, Sardari, & Mofrad, 2015). Dasdag et al. exposed male Wistar rats to 2.4 GHz microwave radiation for 24 hours a day for a year and found increased head defects in sperm, and altered reproductive physiology, including decreases in weight of the epididymis and seminal vesicles, seminiferous tubules diameter, and tunica albuginea thickness in the exposed group (Dasdag, Taş, Akdag, & Yegin, 2015). Rat testes were also examined by Atasoy et al. after exposing male Wistar rats to 2.4 GHz microwaves for 24 hours a day for 20 weeks (Atasoy, Gunal, Atasoy, Elgun, & Bugdayci, 2013). This group found significant increases in serum 8-hydroxy-2'-deoxyguanosine levels and 8-hydroxyguanosine staining in the testes of the exposed group indicating DNA damage.

Several studies investigated the effects of Wi-Fi exposure during pregnancy and in pre- and post-natal and developing rats and mice. Sambucci et al. found no effect on pregnancy outcome or immune system development in newborn C57BL/6 strain mice following exposure to Wi-Fi at an SAR of 4 W/kg for two hours a day for 14 consecutive days starting five days after mating (Sambucci et al., 2010). No significant differences were found between exposed and unexposed groups when comparing spleen cell number, B-cell frequency, or antibody serum levels. A later study by the same group exposed newborn mice to two different SAR levels – 0.08 W/kg and 4 W/kg – for two hours a day, five days a week, for five weeks (Sambucci et al., 2011). The only significant difference between the exposed and sham-exposed groups was reduced IFN-γ production in spleen cells in male mice exposed to microwaves at an SAR of 4 W/kg. The same group exposed pregnant mice at an SAR of 4 W/kg for two hours a day starting five days after mating until one day before delivery and found no significant differences between offspring from the exposed and unexposed groups with regard to indicators of T cell development and function (Laudisi et al., 2012). Based on these three studies, the authors conclude that there is no sufficient evidence to suggest that pre-natal and early post-natal exposure to Wi-Fi RF-EMR incurs any negative effects on immune system development.

Another research group examined *in utero* and early life exposure to Wi-Fi and its potential effects on various aspects of development. Poulletier de Gannes et al. exposed pregnant Wistar rats to a 2.45 GHz Wi-Fi signal for two hours a day, six days a week, for 18 days at three SAR levels (0.08, 0.4, and 4 W/kg) in addition to control and sham-exposed groups (Poulletier de Gannes et al., 2012). After observation for 28 days after delivery, no abnormalities in the rat pups or teratogenic effects were observed at all three levels of exposure. Aït-Aïssa et al. also exposed pregnant Wistar rats to 2.45 GHz at the same three SARs for two hours a day, five days a week from day six to day 21 of gestation; newborn rats were exposed from birth to 35 days (Aït-Aïssa et al., 2012). Enzyme-linked immunosorbent assays were completed for sera collected from the pups but no change in humoral response was observed, indicating no effect of RF-EMR on the immune system at any level of exposure. Another study was conducted where male and female Wistar rats were exposed to 2.45 GHz Wi-Fi radiation for one hour a day, six days a week for three weeks before mating and three weeks afterward at SARs of 0.08 and 4 W/kg in addition to a sham-exposed group (Poulletier de Gannes et al., 2013). No abnormalities were found in the reproductive organs of both male and female rats, and no abnormalities in fetal development were detected at any of the exposure levels tested.

The effects of Wi-Fi exposure *in utero* and during early life were also assessed by a group in Turkey. Özorak et al. exposed female Wistar rats and their newborn male offspring to 2.45 GHz, 900 MHz, and 1800 MHz RF-EMR (the latter two frequencies are commonly used by mobile phones) at an SAR of 0.1 W/kg for an hour a day through the experiment, during which kidney and testes samples were taken at four, five, and six weeks of exposure (Özorak et al., 2013). The results of the study demonstrated increased lipid peroxidation and iron levels, and decreased total antioxidant status, copper, and GSH values among the exposed groups, indicating potential oxidative damage. A year-long study was later conducted by Yüksel et al., with exposure to pregnant Wistar rats at the same frequency bands and SAR, which found decreased prolactin, estrogen, and progesterone levels in the plasma of maternal rats and their offspring, and increased oxidative stress in the uteri of maternal rats in the exposed groups (Yüksel, Nazıroğlu, & Özkaya, 2015). Çelik et al. also exposed pregnant Wistar rats and their newborns to 2.45 GHz radiation at the same SAR for one hour a day, five days a week, from pregnancy until pups were three weeks of age (Çelik, Kahya, & Nazıroğlu, 2015). Results from this study found reduced glutathione peroxidase, glutathione, and antioxidant vitamin concentrations in the exposed groups, indicating oxidative stress to the brain and liver.

A handful of studies examined the effects of Wi-Fi exposure on the brains of mice and rats. Banaceur et al. compared 2.4 GHz exposure in wild type and 3xTg-AD transgenic mice at an SAR of 1.6 W/kg for two hours a day for a month (Banaceur, Banasr, Sakly, & Abdelmelek, 2013). The transgenic mice in this experiment were bred to develop Alzheimer's-like cognitive impairment. Wi-Fi exposure actually improved performance of cognitive tasks in these mice, leading the researchers to conclude that RF-EMR exposure may play a memory-enhancing role in Alzheimer's disease (Banaceur et al., 2013). Dasdag et al. examined micro RNA (miRNA) expression in brain tissue of male Wistar rats after exposure to 2.4 GHz radiation for 24 hours a day for 12 months at an estimated whole-body SAR of 141.4 μW/kg (Dasdag, Akdag, et al., 2015). This experiment determined that expression of some miRNAs were lower in the exposed group than in the sham-exposed group. Because some diseases may originate from altered expression of some miRNAs, the results of this study indicate the possibility of the development of neurodegenerative diseases from long-term exposure to Wi-Fi RF-EMR. Ghazizadeh and Nazıroğlu tested the effect of 2.45 GHz Wi-Fi radiation in male Wistar rats and found Wi-Fi is involved in oxidative stress effects in certain types of neurons in the brain (Ghazizadeh & Nazıroğlu, 2014).

Other potential effects of Wi-Fi exposure have been tested. Fasseas et al. examined the effect of RF-EMR from several sources in *C. elegans* (Fasseas et al., 2015), including mobile phones, cordless landline phones, and Wi-Fi routers. Exposure was set below ICNIRP guidelines but no statistically significant changes in growth, fertility, lifespan, memory, gene expression, apoptosis, or reactive oxygen species were found. Aynali et al. investigated the possible protective effect of melatonin on oxidative stress in the throat cells of male Wistar rats exposed to 2.45 GHz Wi-Fi for one hour a day for 28 days at an average SAR of 0.1-W/kg and found lowered glutathione peroxidase activity and increased lipid peroxidation in the Wi-Fi exposed groups, again suggesting oxidative stress (Aynali et al., 2013). A similar protective effect of melatonin on Wi-Fi exposure was investigated by Tök et al. (Tök, Nazıroğlu, Doğan, Kahya, & Tök, 2014). The lens of male Wistar rats exposed to 2.45 GHz Wi-Fi for one hour a day for 30 days had higher lipid peroxidation levels and lower glutathione peroxidase activity than those in the unexposed groups. While Wi-Fi exposure induced some indicators of oxidative stress, melatonin supplementation decreased those effects. Saili et al. found increased heart rate and arterial blood pressure and altered heart rhythm in male rabbits exposed to Wi-Fi for one hour, demonstrating acute effects of Wi-Fi on the cardiovascular system (Saili et al., 2015). Çiftçi et al. found exposure to 2.45 GHz Wi-Fi at an average SAR of 0.009 W/kg for 2 hours a day *in utero* and during lactation does not interfere with the development of teeth and surrounding tissues but may alter the elemental composition of the teeth (Çiftçi, Kırzıoğlu, Nazıroğlu, & Özmen, 2015).

In vivo studies: human

To date, the body of research on the potential adverse effects of Wi-Fi exposure in humans is currently extremely limited and shows mixed results. Papageorgiou et al. examined the effect of Wi-Fi exposure in male and female subjects while the subjects were completing a working memory task known as the Hayling Sentence Completion test (Papageorgiou et al., 2011). Scalp electrodes recorded P300 event-related potentials, which are linked to attention and working memory. These signals were found to be significantly lower in the presence of RF-EMR. In a non-peer-reviewed study, Maganioti et al. created a Faraday room in which male and female subjects completed a Wechsler test for memory while exposed to a 2.4 GHz Wi-Fi signal and wearing scalp electrodes for an electroencephalogram (EEG) (Maganioti et al., 2010). The researchers saw reduced EEG energies of female subjects, but not male subjects, indicating possible gender-related differences in exposure to Wi-Fi and its effects on brain activity. Average SAR was not specified in either study. Zentai et al. also investigated cognitive function in subjects completing a computerized psychomotor vigilance test (PVT) after being exposed to 2.4 GH Wi-Fi at an SAR of 99.22 mW/kg for one hour (Zentai et al., 2015). Spontaneous awake electroencephalographic (sEEG) activity was also measured. No differences were found between the exposed and unexposed groups with regard to EEG data or reaction time in the PVT task. Summary of *in vivo* studies is seen in Table 1.

Summary of Literature

Table 1: Summary of in-vivo studies.

Author/Year	Title	Study Population	Outcome/Main Results
Fasseas 2015	Response of Caenorhabditis elegans to wireless devices radiation exposure	C. elegans	No effects
Maganioti 2010	Wi-Fi electromagnetic fields exert gender related alterations on EEG	male and female human subjects	Reduced energy of Alpha and Beta bands in EEGs of females only
Papageorgiou 2011	Effects of wi-fi signals on the p300 component of event-related potentials during an auditory hayling task	male and female human subjects	P300 event-related potentials found to be significantly lower in the presence of RF-EMR
Shahin 2014	2.45-GHz microwave irradiation adversely affects reproductive function in male mouse, Mus musculus by inducing oxidative and nitrosative stress	male Swiss strain mice	Significant decrease in sperm count and sperm viability, decrease in seminiferous tubule diameter and degeneration of seminiferous tubules, reduction in testicular 3β HSD activity and plasma testosterone levels, increased expression of testicular i-NOS
Shokri 2015	Effects of Wi-Fi (2.45 GHz) Exposure on Apoptosis, Sperm Parameters and Testicular Histomorphometry in Rats: A Time Course Study	male Wistar rats	Decrease in sperm parameters in a time dependent pattern; number of apoptosis-positive cells and caspase-3 activity increased in the seminiferous tubules of exposed rats; reduced seminal vesicle weight reduced in exposed groups
Aynali 2013	Modulation of wireless (2.45 GHz)-induced oxidative toxicity in laryngotracheal mucosa of rat by melatonin	male Wistar rats	Apparent protective effect of melatonin; radiation-exposed groups had higher lipid peroxidation levels, lower glutathione peroxidase activity

Banaceur 2013	Whole body exposure to 2.4 GHz WIFI signals: effects on cognitive impairment in adult triple transgenic mouse models of Alzheimer's disease (3xTg-AD)	wildtype and 3xTg-AD transgenic mice	Beneficial effect of Wi-Fi on anxiety; no difference in Flex field test
Laudisi 2012	Prenatal exposure to radiofrequencies: effects of WiFi signals on thymocyte development and peripheral T cell compartment in an animal model	female C57BL/6 mice and offspring	No effects
Sambucci 2010	Prenatal exposure to non-ionizing radiation: effects of WiFi signals on pregnancy outcome, peripheral B-cell compartment and antibody production	female C57BL/6 mice and offspring	No effects
Sambucci 2011	Early life exposure to 2.45GHz WiFi-like signals: effects on development and maturation of the immune system	female C57BL/6 mice and offspring	Reduced IFN-γ production in spleen cells from exposed (SAR 4 W/kg) male offspring
Saili 2015	Effects of acute exposure to WIFI signals (2.45GHz) on heart variability and blood pressure in Albinos rabbit	male rabbits	Exposure to Wi-Fi affects heart rhythm, blood pressure, and catecholamine efficacy on cardiovascular system
Aït-Aïssa 2012	In utero and early-life exposure of rats to a Wi-Fi signal: screening of immune markers in sera and gestational outcome	female Wistar rats and offspring	No effects
Çelik 2015	Oxidative stress of brain and liver is increased by Wi-Fi (2.45GHz) exposure of rats during pregnancy and the development of newborns	female Wistar rats and offspring	Wi-Fi exposure induced oxidative stress in the brain and liver of developing rats

Çiftçi 2015	Effects of prenatal and postnatal exposure of Wi-Fi on development of teeth and changes in teeth element concentration in rats. [corrected]	female Wistar rats and offspring	No effects
Dasdag 2015	Effects of 2.4 GHz radiofrequency radiation emitted from Wi-Fi equipment on microRNA expression in brain tissue	male Wistar rats	Changed expression of some of the examined miRNAs
Dasdag 2015	Effect of long-term exposure of 2.4 GHz radiofrequency radiation emitted from Wi-Fi equipment on testes functions	male Wistar rats	Altered general morphology of rat testes
Ghazizadeh 2014	Electromagnetic radiation (Wi-Fi) and epilepsy induce calcium entry and apoptosis through activation of TRPV1 channel in hippocampus and dorsal root ganglion of rats	male Wistar rats	Epilepsy and Wi-Fi are involved in Ca2+ influx and oxidative stress-induced hippocampal and DRG death through activation of TRPV1 channels
Özorak 2013	Wi-Fi (2.45 GHz)- and mobile phone (900 and 1800 MHz)-induced risks on oxidative stress and elements in kidney and testis of rats during pregnancy and the development of offspring	female Wistar rats and male offspring	Increased lipid peroxidation and oxidizable iron content and decreased antioxidant trace elements (copper and zinc), TAS, and GSH during kidney and testis development
Poulletier de Gannes 2012	Effect of in utero wi-fi exposure on the pre- and postnatal development of rats	female Wistar rats and offspring	No effects
Poulletier de Gannes 2013	Rat fertility and embryo fetal development: influence of exposure to the Wi-Fi signal	male and female Wistar rats	No effects

Tök 2014	Effects of melatonin on Wi-Fi-induced oxidative stress in lens of rats	male Wistar rats	GSH-Px activities were significantly lower in Wi-Fi group
Yüksel 2015	Long-term exposure to electromagnetic radiation from mobile phones and Wi-Fi devices decreases plasma prolactin, progesterone, and estrogen levels but increases uterine oxidative stress in pregnant rats and their offspring	female Wistar rats and offspring	EMR exposure decreased the prolactin, estrogen, and progesterone levels in the plasma of maternal rats and their offspring; EMR-induced oxidative stress in the uteri of maternal rats increased during the development of offspring
Atasoy 2013	Immunopathologic demonstration of deleterious effects on growing rat testes of radiofrequency waves emitted from conventional Wi-Fi devices	male Wistar rats	Increases in serum 8-hydroxy-2′-deoxyguanosine levels and 8-hydroxyguanosine staining in the testes; decreased levels of catalase and glutathione peroxidase activity in the exposed group
Zentai 2015	No Effects of Acute Exposure to Wi-Fi Electromagnetic Fields on Spontaneous EEG Activity and Psychomotor Vigilance in Healthy Human Volunteers	male and female human subjects	No effects
Nazıroğlu 2013	Recent reports of Wi-Fi and mobile phone-induced radiation on oxidative stress and reproductive signaling pathways in females and males	(review)	There is no evidence to this date to support an increased risk of female and male infertility related to EMR exposure
Foster 2013	Wi-Fi and health: review of current status of research	(review)	No basis to anticipate that Wi-Fi exposure will cause any biological effects; RF exposures below international (ICNIRP or IEEE) exposure limits have not been shown to produce any health hazard

Table 2: Summary of in-vitro studies.

Author/Year	Title	Study Population	Outcome/Main Results
Çiğ 2015	Investigation of the effects of distance from sources on apoptosis, oxidative stress and cytosolic calcium accumulation via TRPV1 channels induced by mobile phones and Wi-Fi in breast cancer cells	human cancer cells	Wi-Fi and mobile phone EMR placed within 10 cm of the cells induced excessive oxidative responses and apoptosis via TRPV1-induced cytosolic Ca2 + accumulation in the cancer cells
Avendaño 2012	Use of laptop computers connected to internet through Wi-Fi decreases human sperm motility and increases sperm DNA fragmentation	semen from healthy human donors	Significant decrease in progressive sperm motility and an increase in sperm DNA fragmentation
Oni 2011	Effects of radiofrequency radiation from WiFi devices on human ejaculated sperm	semen from males aged 20-30	Sperm concentration, motility and morphology grading of the sperm were significantly affected by exposure to Wi-Fi
Yildirim 2015	What is harmful for male fertility: cell phone or the wireless Internet?	semen from patients at infertility clinic	Negative correlation between wireless internet usage duration and the total sperm count ($r = -0.089$, $p = 0.039$)

Table 3: Summary of exposure assessments.

Author/Year	Title	Study Population or Geographic Area	Outcome/Main Results
Valič 2015	Typical exposure of children to EMF: exposimetry and dosimetry	21 children under the age of 17 + voxel model	SAR values for the typical and the worst-case situation show low exposure under ICNIRP guidelines
Martínez-Búrdalo 2009	FDTD assessment of human exposure to electromagnetic fields from Wi-Fi and Bluetooth devices in some operating	high-resolution model of the human head and torso	Exposure levels from Wi-Fi are lower than those obtained from mobile phone exposure; field and SAR values are far below the limits established by IEEE and ICNIRP guidelines

	situations		
Joseph 2010	Estimation of whole-body SAR from electromagnetic fields using personal exposure meters	human spheroid phantoms - 1 year old, 5-year-old child, 10-year-old child, average woman, average man	Highest whole body SAR values were obtained for the 1 year old; all values were below restrictions for the general public
Findlay 2010	SAR in a child voxel phantom from exposure to wireless computer networks (Wi-Fi)	child voxel (graphic) model	Calculated SARs below ICNIRP restrictions (19.1 μW/kg for plane wave, 1.8 mW/kg for dipole antenna, and 3.99 mW/kg in the torso and 5.7 mW/kg in the head for laptop mounted antenna) and exposures to Wi-Fi represent about 1% of that of mobile phones
Vermeeren 2013	Spatial and temporal RF electromagnetic field exposure of children and adults in indoor micro environments in Belgium and Greece	Greece and Belgium	All instantaneous and maximal exposures satisfied international exposure limits; highest average exposures were found in office environments and lowest in homes and in schools; exposure in offices was mainly due to mobile telecommunications whereas in home environments, DECT and Wi-Fi 2G were the dominating sources
Foster 2007	Radiofrequency exposure from wireless LANs utilizing Wi-Fi technology	U.S., France, Germany, Sweden	Measured Wi-Fi signal levels were very far below international exposure limits (IEEE C95.1-2005 and ICNIRP)
Schmid 2007	Exposure caused by wireless technologies used for short-range indoor communication in homes and offices	Austria	None of the devices considered in this study exceeded the limits according to the ICNIRP guidelines

Bolte 2012	Personal radiofrequency electromagnetic field measurements in The Netherlands: exposure level and variability for everyday activities, times of day and types of area	Netherlands	Mean total exposure was 0.277 V/m with 37.5% of power density from mobile phones, 31.7% from cordless phones, 14.1% from Wi-Fi, 12.7% from base stations, and 3% from FM
Joseph 2008	Characterization of personal RF electromagnetic field exposure and actual absorption for the general public	Belgium	Indoor exposure in office environments can be higher than outdoor exposure; 95th percentiles of field values due to Wi-Fi ranged from 0.36 to 0.58 V/m
Tomitsch 2015	Exposure to electromagnetic fields in households--trends from 2006 to 2012	Austria	Median RF-EMF exposure from WLAN increased from 0.00 µW/m2 in 2006 to 0.46 µW/m2 in 2012; increase in number of installed and activated WLAN routers from 2006-2012; median exposure in households with activated WLAN was 4.08 µW/m2 and the median of the 105 households with no, switched off, or deactivated WLAN was 0.07 µW/m2
Urbinello 2014	Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities	Switzerland and Belgium	Mobile phone handsets and base stations contributed the most to overall RF exposure in all situations; highest exposure levels occurred in public transport (trains); all exposure levels were far below reference levels proposed by ICNIRP
Verloock 2010	Procedure for assessment of general public exposure from WLAN in offices and in wireless sensor network testbed	Belgium	Average background exposure to WLAN (WiLab off) is 0.12 V/m, with a 95th percentile of 0.90 V/m; with the WiLab in operation, average exposure increases to 1.9 V/m, with a 95th percentile of 4.7 V/m; all values were well below the ICNIRP guidelines

Verloock 2014	Assessment of radio frequency exposures in schools, homes, and public places in Belgium	Belgium	Average and maximal total electric-field values in schools, homes, and public places were 0.2 and 3.2 V/m (Wi-Fi), 0.1 and 1.1 V/m (telecommunication), satisfying the ICNIRP reference levels; in the schools considered, the highest maximal and average field values were due to internal signals (Wi-Fi)
Viel 2009	Radiofrequency exposure in the French general population: band, time, location and activity variability	France	Highest mean exposure resulted from FM sources (0.044 V/m), followed by WiFi-microwaves (0.038 V/m), cordless phones (0.037 V/m), and mobile phones (UMTS: 0.036 V/m, UMTS: 0.037 V/m)
Khalid 2011	Exposure to radio frequency electromagnetic fields from wireless computer networks: duty factors of Wi-Fi devices operating in schools	UK	Duty factors of individual laptops were considerably less than those of the access points; the maximum time-averaged power density from a laptop would be 220 μW/m2, at a distance of 0.5 m, and the peak localized SAR predicted in the torso region of a 10 year old child model, at 34 cm from the antenna, would be 80 μW/kg, which is lower than ICNIRP guidelines
Lanham 2015	Public Exposure from Indoor Radiofrequency Radiation in the City of Hebron, West Bank-Palestine	Palestine	Maximum total power density found at any location was about 2.3 x 10-2 W/m2 with a corresponding exposure quotient of about 0.01, indicating compliance with the guidelines of ICNIRP; relative contributions to the total exposure were 46% from FM radio, 26% from GSM900, 15% from DECT phones, 9% from WLAN, 3% from unknown sources, and 1% from TV broadcasting; RF sources located outdoors contribute about 73% to the population exposure indoors

Peyman 2011	Assessment of exposure to electromagnetic fields from wireless computer networks (wi-fi) in schools; results of laboratory measurements	UK	The spherically-integrated radiated power (IRP) ranged from 5 to 17 mW for 15 laptops in the 2.45 GHz band and from 1 to 16 mW for eight laptops in the 5 GHz band; for wall mounted access points, power ranged from 3 to 28 mW for 12 access points at 2.4 GHz and from 3 to 29 mW for six access points at 5 GHz; all vales were under ICNIRP guidelines

Discussion

Although the current body of literature specifically regarding Wi-Fi exposure is still extremely limited compared to the existing research into RF-EMR from mobile phones, it is encouraging that more scientists have started investigating the issue in the last decade. Still, it is clear that more work needs to be done to further elucidate the true, or lack of, biological effects of Wi-Fi exposure. Thus, this review does not provide a definitive answer as to whether schools in Maryland should opt for hardwired computers, but instead provides a summary of the state of the science completed to-date on the issue.

A large portion of the studies in this review are *in vitro* studies of mammals, particularly rats and mice. The four studies examining effects of Wi-Fi on sperm and reproductive organs of rats and mice (Atasoy et al., 2013; Dasdag, Taş, et al., 2015; Shahin et al., 2014; Shokri et al., 2015) found significant differences between exposed and unexposed groups, indicating potential negative effects of Wi-Fi exposure on male fertility. This was the only group of studies that showed consistent biological effects due to exposure. Investigations into other hypothesized biological effects resulted in more mixed or no conclusions. Studies of Wi-Fi exposure on pregnant rats and mice and their newborn offspring yielded no significant differences between exposed and unexposed test animals when measuring teratogenic or developmental outcomes (Aït-Aïssa et al., 2012; Laudisi et al., 2012; Poulletier de Gannes et al., 2012, 2013; Sambucci et al., 2010, 2011). There is some indication of oxidative stress from prenatal to early life, however two out of three of these studies exposed the test animals to multiple RF-EMR frequencies, including those from mobile phones (Çelik et al., 2015; Özorak et al., 2013; Yüksel et al., 2015).

In vitro studies of human sperm show some signs of cell damage as a result of Wi-Fi exposure, although one study measured exposure from a questionnaire instead of an actual experiment (Yildirim et al., 2015) and the other two studies (Avendaño et al., 2012; Oni et al., 2011) conducted their experiments with an unknown dose, specifying only the distance from which the sperm were placed from the Wi-Fi source. In general, study designs in many of the articles in this review were lacking and could be improved in future experiments. Overall, the literature on this topic is not of high enough quality to make a convincing argument for biological effects of Wi-Fi on sperm function and quality.

Population-level exposure assessments in the literature provide some insight into the proportion of daily exposure to RF-EMR from Wi-Fi frequencies. For the most part, studies found that signals from mobile phones dominate exposure in both indoor and outdoor settings (Bolte & Eikelboom, 2012; W. Joseph et al., 2008; Vermeeren et al., 2013; Viel et al., 2009). In some cases, FM radio signals make up the highest proportion of overall RF exposure, but 900 and 1800 MHz mobile phone signals follow close behind (Lahham et al., 2015). When evaluating Wi-Fi alone, average power density measured in schools, homes, and public places was well below ICNIRP guidelines (Foster, 2007; W. Joseph et al., 2008; Peyman et al., 2011; Verloock et al., 2014, 2010). Voxel and phantom models of RF-EMR absorption found that with a typical power density and duty cycle scenario in a classroom, the estimated SAR in a child's torso would also be below ICNIRP reference levels (Findlay & Dimbylow, 2010; Wout Joseph et al., 2010; Khalid et al., 2011).

A noticeable gap in the literature is in human studies – both *in vivo* and large scale epidemiologic studies. The existing studies using mammals as test subjects in exposure experiments are not adequate for determining true human health risk, especially with the mixed quality of studies included in this review. As several epidemiologic studies have already been conducted regarding the risks of mobile phone use, as cited in the IARC monographs of EMFs (Baan et al., 2011), the same must be done for Wi-Fi. Additionally, although some groups have begun to incorporate the 5 GHz Wi-Fi band in exposure studies, all studies moving forward should consider both frequencies. Though the majority of commercially available Wi-Fi access points and routers still operate at 2.45 GHz by default, they are increasingly supporting both frequencies for better performance (Institute of Electrical and Electronics Engineers, 2013). Although Wi-Fi devices currently operate at two frequencies, additional frequency bands below 2.45 GHz or above 5 GHz may be added for devices in the future. This would potentially push the spectrum of WLAN solidly into radiofrequency (with lower frequencies) or further into microwave territory (higher frequencies). The health effects of an expanding Wi-Fi spectrum need to be addressed if and when the time comes.

Another consideration for future studies is to conduct more exposure assessments in the US; only one exposure assessment study in this review was partially completed in the US (Foster, 2007). The issue of RF-EMR in general seems to have more traction in Europe than in the US, but with the growing concern from parents and advocates, it is important to conduct more studies in settings that reflect the lives of children in the US. This includes exposure assessments in rural, suburban, and urban areas, as well as different school settings. Since exposure to RF-EMR seldom, if ever, occurs from one frequency band at a time, more cumulative exposure and risk assessments must be completed to assess the combined effects of exposure to multiple sources of radiation at the same time. It is also worth considering the cumulative effects of RF-EMR exposure in conjunction with other environmental hazards, as many health outcomes, such as cancer, are seldom due to just one cause.

More robust methods and exposure systems must be developed if more *in vivo* animal studies are to be completed. Because this research area is relatively new, there is no established standard for creating exposure systems to test for biological effects and thus there is a lack of consistency across studies. Currently, the only consistency in exposure systems is seen within research groups who use the same system across multiple studies. The Wi-Fi exposure itself must also be better characterized for use in experiments. As seen in this review, some research groups employed complex techniques to estimate an SAR in their test animals, while others used more arbitrary measurements such as distance from the access point. Test animals are also kept in optimal conditions during the experiment, including adequate nutrition and antioxidants in their feed. Given that several studies found oxidative stress effects from Wi-Fi exposure, supplements in the food may have attenuated results. Future studies should also test cumulative exposure from multiple sources of RF-EMR, as well as cumulative exposure to other agents that cause oxidative stress. Finally, as with human studies, future animal studies also need to include the 5 GHz Wi-Fi frequency band moving forward.

There were some limitations in the implementation of this literature review. Due to time restrictions, a more thorough search of the available literature was not possible. Some literature may not have been captured using the search strategy described above; some articles do not use the word “Wi-Fi” but instead describe exposures by the wavelength only (e.g. “2.45 GHz microwaves”) and some articles may not have been searchable using PubMed/MEDLINE. Additionally, studies with null results may not have been published, particularly with a new and sensitive topic such as Wi-Fi. Although several studies in this review showed no effects, it is possible there is more unpublished evidence of null effect that were not included in this review. The vast majority of the research available on Wi-Fi is based on animal studies, adding uncertainty when extrapolating the results to humans, particularly when determining typical exposure to Wi-Fi across different populations.

All studies cited in this review either used SARs below ICNIRP guidelines (in the case of *in vivo* and *in vitro*) or found that measured and simulated exposure were well below limits (in the case of modeled and actual exposure assessments). However, this does not provide any reassurance for those who insist that the ICRNIRP guidelines and FCC standards are inadequate for public health protection and must be revisited after close to 20 years of new research (Gandhi et al., 2012; McInerny, 2013; Sage & Carpenter, 2009; US Government Accountability Office, 2012). Calls for revision also stress the importance of developing exposure guidelines separately for children and adults, based on some evidence that children may absorb more radiation than adults (Wout Joseph et al., 2010; Morgan, Kesari, & Davis, 2014; Morris, Morgan, & Davis, 2015). ICNIRP is currently revising its guidelines, though with no anticipated completion date (International Commission on Non-Ionizing Radiation Protection, 2016). The FCC opened a review of their current RF-EMR standards in 2013 but no updates to regulations have been made to date (Federal Communications Commission, 2013).

Although teachers and staff, not just students/children, are exposed to RF-EMR in schools equipped with Wi-Fi, the main research question in this report is the issue of children’s exposure specifically in response to the urging of concerned parents. Children are, of course, more vulnerable to environmental exposures in general and Wi-Fi is likely no exception. Recommendations by CEHPAC and any potential policy changes in Maryland leading to reduced exposure would have an overall protective effect on the school environment that would not only benefit children, but adults in that environment as well.

A simple solution for those who favor the precautionary approach is to simply hardwire schools instead of opting for Wi-Fi enabled laptops. However, this could potentially have a negative impact on teachers' ability to access the wide range of educational resources and content available on the internet. In a recent Pew survey, 92% of teachers said the internet has a major impact on their ability to access materials for teaching, and the majority of teachers surveyed said they often use wireless devices such as tablets, mobile phones, and e-book readers in addition to laptops in the learning process (Purcell, Heaps, Buchanan, & Friedrich, 2013). Access to the internet is perceived as an essential part of modern education, as evidenced by President Obama's ConnectEd Initiative to ensure all students in the US will have access to broadband internet by 2018 (The White House Office of the Press Secretary, 2013). Administrators and health experts must weigh the benefits of fully connected schools with the unknown possible biological effects of Wi-Fi exposure.

Conclusion

Wi-Fi exposure, particularly in schools, is a contentious issue that will remain controversial as more studies are conducted regarding its potential biological effects. The current literature provides inconclusive evidence that, for the most part, points to an absence of adverse health consequences from long-term and acute exposure to Wi-Fi frequencies. Completed exposure assessments show typical and worst-case scenario exposures fall well below US and international reference levels. However, those guidelines and standards have their own limitations; they are almost two decades old, do not reflect current science, and do not take into account vulnerable populations such as children. Wi-Fi connected classrooms have huge advantages both for students and teachers, but may not be worth the trade-off of possible health effects later in life. It is clear that more and better studies are needed, particularly large-scale epidemiological studies, before a definitive conclusion can be reached.

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