ELECTROMAGNETIC FIELDS (EMFs): SCIENTIFIC EVIDENCE REVIEW, REGULATORY ANALYSIS AND POLICY RECOMMENDATIONS.

DAVID O. CARPENTER, MD, UNIVERSITY AT ALBANY

Microwave Radiofrequency Electromagnetic Fields

Microwaves are the part of the EMF spectrum that has frequencies between 300 MHz and 300 GHz. Thus, they have higher frequencies and shorter wavelengths than radio waves but lower frequencies and longer wavelengths than infrared EMF. Microwave ovens usually operate at a frequency of 2.45 GHz, a frequency chosen because it stimulates water movement and thus causes heating. At sufficient intensity all microwaves cause heating.

Microwave communication uses information superimposed upon a carrier sine wave within the 300 MHz to 300 GHa range. There is always an ELF component to RF communication frequencies as well, and some have suggested that this contributes significantly to health effects of microwave communication frequencies (Panagopoulos er al., 2026).

An important consideration regarding evaluation of health effects of RF radiation within this window of frequencies is that technology has changed greatly over recent years. Since diseases such as cancer have a long latency, cancers that appear now may reflect exposures to older technology. Third generation (3G) technology began in the early 2000s and is now shut down. It was used for exploring websites and email. It primarily used the frequency "bands" of 850, 900, 1900 and 2100 MHz. In 2012 4G technology was developed, which is the major one currently in use. It uses both higher and lower frequencies, divided into six "bands", with commonly used frequencies of 799 MHz, 850 MHz, 1.7-2.1 GHz, 1.9 GHz, 2.3 GHz and 2.5 GHz. The frequencies below 1 GHz offer greater range and penetration of objects while frequencies 1.7 – 2.6 GHz provide faster speed and greater data capacity. 5G was developed for use in 2019, and together with 4G allowed greater bandwidth and increased frequencies. Because the higher frequences are more easily blocked by walls, foliage and any other barriers, most current use is a combination of 4G and 5G. Because the 5G signals do not travel as far, the practice has been to have mini-cell towers located within relatively short distances from each other on streets, leading to elevated exposures to both residents and individuals on sidewalks. This practice results in greater exposure to the 4G signals than when they came only from a cell tower. Stand-alone 5G became operational in 2025 and uses frequencies of 900 MHz to 3.6 GHz. It is just now being implemented widely.

The signals from cell phones, cell towers and WiFi are quite similar, that being sine waves with superimposed information. The signals from electronic ("smart") meters are quite different in that these use very brief (about 5 ms pulses) but very high intensity peaks occurring many thousands times a day. There is some evidence that the rapid rise and fall of pulses is particularly provocative.

Human Health Effects of Microwave Radiation:

Cancer: There is strong evidence that excessive use of a cell phone held to the head increases the risk of glioma, glioblastoma and acoustic neuroma [summarized in the Bioinitiative Report (www.bioinitiative.org)]. The strongest evidence is for glioma occurring on the side of the head where a person regularly uses their cell phone. Much of the early work came from Hardell and colleagues (summarized in Hardell and Carlberg, 2015) who found that cell phone use increased risk of glioma [OR = 1.3 (1.1-1.6)] and that the risk increased with more than 25 years of use [OR = 3.0 (1.7-5.2)]. Use of cordless phones also showed a similar risk pattern. The risk of glioma from either type of phone increased with cumulative hours and years of use and were largest on the ipsilateral side of the head where the phone was usually held.

The Interphone study (Interphone Study Group, 2010) used data from 13 countries (but not the US) to investigate use of cell phones and gliomas and meningiomas. They reported that "No increase in risk of glioma or meningioma was observed with use of mobile phones". However, hidden away in supplemental material was the evidence that use of a cell phone for ten years or more resulted in a significant 2.18-fold increase in glioma risk, that use for 1640+ hours resulted in a 1.62-fold elevated risk, and that making more than 270 calls resulted in a 1.31-fold increased risk of glioma.

Belpomme, Hardell et al. (2018) performed a meta-analysis of data from the Hardell studies, the Interphone study group and the CERENAT case-control study (Coureau et al.,2014). They report that cell phone use for 896 – 1640 hours increased risk of gliomas [OR =1.90 (1.31-2.76)] and that the risk was largest on the side of the health where the cell phone was regularly used [OR = 2.54 (1.83-3.52)]. For meningioma they found an elevated but not statistically significant risk for the highest category of cell phone use, but it was significant on the ipsilateral side of the head [OR= 1.49 (1.08-2.06)]. The same pattern applied for acoustic neuroma, where it was significant only ipsilaterally [OR = 2.7 (1.71-4.28)]. Acoustic neuroma is a tumor, not a cancer, of the auditory nerve, and it becomes a space-occupying growth that causes deafness.

Hardell and Carlberg (2009) pooled results from two of their case-control studies and found that age of the individuals starting cell phone use was a major contributing factor. For those under the age of 20 the OR = 5.2 (2.2-12) and for ipsilateral use OR =7.8 (2.2-28) for glioma. There were lower odds ratios for individuals who began cell phone use as young and middle-aged adults, but no significant increase found among those who began use over the age of 50. Risk increased with duration of use. Among individuals with > 1 year cell phone use the glioma OR = 1.4 (1.1-1.8), while for >10 years it was OR = 2.5 (1.4-4.4), and for > 1 but <20 OR = 5.2 (2.2-12). Among individuals diagnosed with glioblastoma, the most malignant form of gliomas, survival was less long among those with greater cell phone usage. The risk for meningioma was less than for glioma but became significant for ipsilateral use (OR = 1.49 (1.08-2.06). For acoustic neuroma the OR = 2.40 (1.39-4.16) and for ipsilateral use was OR=3.18 (1.65-6.12).

These results are particularly important for several reasons regarding the controversies over adverse effects of EMFs. First there is a view expressed by some that RF radiation can only have biological effects if it is sufficiently strong to cause tissue heating. In the US, RF communication is regulated by the Federal Communication Commission, and RF from cell phones, cell towers and WiFi is regulated so that it operates at an intensity that does not cause measurable tissue heating. Many also believe that RF radiation cannot enter the brain through the skull and thus cannot have biological effects on nervous system function. This has been shown to not be the case by Volkow et al. (2011) who measured changes in brain metabolism in humans using deoxyglucose with positron emission tomography. They compared results when a muted but active cell phone was held to the ear as compared to when the cell phone was turned off. Even with no sound the active cell phone held to the ear resulted in an increase in metabolism in the brain near the ear, and even a smaller increase on the contralateral side. There was no change in brain metabolism if the cell phone was not active. Thus, RF from a cell phone at intensities that do not cause tissue heating enters brain tissue and alters brain metabolism.

In 2011 the International Agency for Research on Cancer (IARC, 2011) rated RF radiation as a Group 2B, possible human carcinogen. One of the reasons it was not rated at a higher level was the lack of demonstration that RF caused cancer in animals. That has changed. The National Toxicology Program (NTP) of the National Institutes of Health conducted a study of rats exposed to cell phone-level radiation (NTP, 2016) and found an increase in gliomas of the brain and schwannoma of the heart. Acoustic neuromas are schwannomas resulting from cell phone radiation to the ear, while in the animal studies the whole body was exposed, leading to schwannomas elsewhere. The NTP study also found that long-term exposure of rats to cell phone radiation caused DNA damage. This is important in that DNA damage is a central factor leading to cancer. Later the Ramazzini Institute (Falcioni et

al., 2018) performed a similar animal study but using levels of RF exposure such as people would get living near to a cell tower. They found elevation in rates of the same two tumors as seen in the NTP study. And this is from a much lower level of RF exposure.

These human studies show clearly that RF radiation exposure increases risk of brain cancer and tumors of the auditory nerve and the animal research confirms that conclusion. While there is less evidence regarding other kinds of cancer it is likely that localized exposure to other parts of the body also increases cancer risk, as for example women who wear active cell phones in their bra (West et al., 2013).

Cognitive Function in Children: Because fetuses and children are rapidly growing, they are especially vulnerable to harm from many different exposures. Furthermore, agents that cause changes to genes, growth and development will have life-long effects. There is strong evidence that a child's head absorbs cell phone radiation than an adult because the brain is smaller, their skull thinner and the brain tissue is more conductive because of lower levels of myelin (Gandhi et al., 2012; Fernandez et al., 2018; Bevington, 2026). Harm to children from RF, as for other neurotoxicants, is greatest in the fetal period and very early life (Miguel et al., 2019).

Divan et al. (2012) investigated behavioral problems in 28,745 7-year-old children in relation to the mother's use of a cell phone during pre- and post-natal periods. They found that children born to mothers who used cell phones during gestation exhibited more behavioral problems [OR = 1.5 (1.4-1.7)] than children born to mothers who did not use cell phones. Sudan et el. (2018) combined information from three different birth cohort from Spain, Denmark and Korea. Although there was no association found between frequency of maternal cell phone use and child's cognitive function, there was a pattern in all three cohort for lower cognitive function in children in relation to the highest frequency of maternal cell phone use. Birks et al. (2017) used data from 83,884 mother-child pairs from five different European and Asian cohorts and found the mothers who did not use cell phones during pregnancy were less likely to give birth to a child showing hyperactivity or emotional problems. Setia et al. (2025) made RF measurements in the homes of 105 neonates and followed them for one year. Those living in homes with higher levels of RF did more poorly on outcomes in the cognitive domain for problem solving using the Ages and Stages Questionnaire.

There is also some evidence that older children exposed to RF show more adverse behavioral and cognitive problems than do less exposed children. Calvente et al. (2016) studied Spanish 10-year-old boys in relation to measured RF exposure. While most cognitive and behavioral factors did not show associations, those children with the highest level of RF exposure showed lower scores on verbal expression, comprehension and higher

scores for internalizing, obsessive- compulsive disorder and post-traumatic stress disorder. Foerster et al. (2018) studied two waves of Swiss adolescents from 44 different 7-9th grade schools in relation to modelled RF exposure based on personal RF meters worn by a subset of students. They found decreased memory and cognitive function in relations to elevations in RF exposure. They also reported that use of media that was not associated with RF had no effect. Schoeni et al. (2015) studied memory function in 439 adolescents in relation to use of wireless devices. They found that the cumulative duration of cell phones was associated with a decrease in figurative memory. Cabre-Riera et al. (2021) found that elevated whole-brain RF exposure to Spanish ad Dutch pre-adolescents was associated with lower non-verbal intelligence. Meo et al. (2019) examined cognitive health of 13–16-year-old students in a school close to a cell tower as compared to those in a different with no close cell tower. They found impaired delayed fine and gross motor movements, spatial working memory and attention in the students in the school adjacent to the cell tower. However no behavioral or cognitive effects were found in studies of Dutch (Guxens et al., 2019) or Japanese (Ajmal et al.,) children in relation to RF exposures. Bodewein et al. (2022) have published a systematic review on children and adolescent health effects from RF exposure and have identified a lack of consistency in outcomes and urge that further high-quality research be done.

Cognitive Function in Adults: There is some but less information on cognition in adults upon RF exposure. Vecsei et al. (2018) monitored EEG activity in young adults and administered the Stroop cognitive test in relation to RF exposures. They found no effect on cognitive function but did find a clear decrease in the alpha power of the EEG. Sauter et al. (2025) studied RF effects on cognitive function in a small sample of adults over the age of 60 years and found that overall cognitive performance was not affected by short-term exposure, consistent with the likely greater vulnerability of children. The WHO review on RF exposure and cognitive function (Benke et al., 2024) concluded that there were few studies that provide convincing evidence on the subject but state that there is a need for future investigations. However this review is one of a series of reviews that have been questioned because of underlying assumptions (ICBF-EMF, 2022).

Male Reproductive: It has been known since 2009 (Agarwal et al.; De Juliis et al.) that REF exposure of isolated human sperm causes decrease in sperm viability and motility, and that these effects are mediated by RF-induced oxidative stress. A review by La Vignera et al. (2012) reported that isolated human sperm exposed to RF show decreased motility, more abnormalities and increased oxidative stress, whereas men using cell phones have decreased sperm counts, decreased sperm motility and decreased sperm viability. Rahban et al. (2023) studied 2886 male Swiss military recruits ages 18-22 and determined ejaculate volume, sperm count, viability and morphology in relation to cell phone usage.

They found lower sperm concentration and total sperm count in individuals using their cell phone more than 20 times per day, indicating a 21- 30% increase in risk of infertility based on WHO standards.

WHO sponsored systematic reviews of male fertility in relation to RF exposure [Kenny et al., 2024; Cordelli et al., 2024) concluded that the evidence for an adverse impact of RF exposure on male fertility is uncertain, and that further study is needed. However, these, as well as the other reviews sponsored by WHO are of questionable accuracy as discussed below (ICBE-EMF, 2022; Melnick et al., 2026).

Female Reproduction: There has been less attention to the effects or RF on female as compared to male reproduction. Lu et al. (2017) reported on low birth weight among children born to 361 Japanese women in relation to maternal cell phone use and found that the mean birth weight was less in mothers who used their cell phone excessively. Tsama et l. (2019) analyzed the effects of cell phone use on birth outcomes from four countries (n = 55,507). While there was no relation to fetal growth or birth weight, there was a small but significant increase of giving birth at a lower gestational age and shorter pregnancy duration. Zhou et al. (2021) investigate effects of RF exposure from appliances and risk of congenital heart disease and reported significant elevated risk to children (n = 2339) of mothers exposed to computers, microwave ovens and induction cookers. They also report that risk was reduced if the mothers wore a radiation protection suit. There have also been several studies of reproductive effects of women occupationally exposed to short-waves (3 to 30 MHz), reporting elevated rates of miscarriage (Quellet-Hellstrome and Stewart, 1993), delayed time to pregnancy, increased still births and low birth weight (Shaw and Farrow, 2014; Lerman et al., 2001) and elevated rates of fetal death (Kallen et al., 1982). While none of these studies show striking effects it is clear that more research on RF effects on female reproduction is needed (Johnson et al., 2024)..

Electro-hypersensitivity (EHS): EHS, or "microwave illness", is a syndrome where some people develop excessive fatigue, headache, weakness, memory impairment tinnitus, dizziness, irritability, sleep impairment and general feeling of ill health upon exposure to high levels of EMFs. It is a disease fitting the category of "idiopathic environmental intolerance" or "medical unexplained illness" that includes other diseases such as multiple chemical sensitivity, chronic fatigue syndrome, fibromyalgia and Gulf War Illness. The syndrome was described by Frey in 1971. Not every person who ascribed their symptoms to EMFs has EHS, since blinded exposures do not always show responses, but in a subset of persons blinded exposures do elicit symptoms (Rea et al., 1991). The prevalence of EHS is believed to be between less than 1 to more than 13% in different

countries and is increasing, perhaps due to awareness of the condition (Hallberg and Oberfeld, 2006). It is more common in women but also seen in men and children.

During the Cold War the Soviets irradiated the US Embassy in Moscow with microwaves (2.5-4.0 GHz). This caused both personal and political concern in that the Soviet Union had much more stringent standards for microwave exposures than the US. The US Congress solicited a study of embassy employees and their dependents looking for cancer and other adverse health effects. This study did not find an elevation in cancer, which is not surprising given that there is a long latency between any environmental exposure and the development of cancer, but did find that embassy staff reported more depression, irritability, difficulty in concentrating and more memory loss (see review by Carpenter, 2015). There was also some evidence for pregnancy problems among women in the Moscow embassy as compared to those is other embassies (Goldsmith, 1997).

Millimeter EMFs, radar, 5G and 6G:

Millimeter EMF are frequencies between 30 to 300 GHz, which is the range used by 5G. These frequencies are in use currently as in radar, microwave links, and airport security screening. The use of microwave technology was first developed during World War II in the form of radar.

Radar uses microwaves to locate weather patterns and air traffic or determine how fast you are driving and does so by sending a microwave beam and measuring the reflected return which provides information on distance of objects. Police radar, for example, uses 34 GHz. This is the technology being applied in the development of self-driving vehicles, where microwave beams detect objects ahead and send back that information. These frequencies penetrate the body much less than do lower frequencies but can cause heating of the skin.

Health effects from radar EMFs:

Cancer: A report following Belgium military radar operators (n – 4,417) compared to military personnel not using radar (n = 2,932) from 1963 to 1994 found significantly more cancers [RR = 1.22 (1.03-1.47) and significantly more “symptoms for ill-defined conditions” [RR =3.51 (1.19-10.3)] Of the cancers there were increased deaths from hematolymphoid cancers [RR= 7.22 (1.69-47.9)] (Degrave et al., 2009). Peleg et al. (2023) found similar elevations in hematolymphoid cancers in Israeli military personal exposed to radar and suggest that the high peak power if the radar pulses is a factor. They also suggest that unlike the situation with cell phone exposures, when the whole body is exposed, the cancer risk is greatest for hematolymphoid cancers rather than brain cancer.

EHS: The use of microwave technology was first developed during World War II in the form of radar. There have been several reports of illnesses developed among military personnel who were accidentally exposure to excessive radar field (summarized by Carpenter, 2015). The symptoms included headaches, insomnia, fatigue, difficulty concentrating, irritability, nausea, diarrhea and photosensitivity. Although the exposures were brief, for most individuals the symptoms continued for as long as the personnel were followed, which was over a period of at least several years. This is clearly the EHS syndrome and indicates that even though very high frequency EMF do not penetrate the human body to the degree that those from 3G and 4G do, high frequency EMFs can cause EHS.

Because the role-out of 5G and 6G is so recent there has been little study of health effects and it is urgently needed. In spite of the fact that these higher frequency forms of EMF do not penetrate as much as those of lower frequency the above information is indicative of adverse health effects upon exposure.

References:

Carpenter DO (2015) The microwave syndrome or electro-hypersensitivity: historical background. Rev Environ Health 30: 217-222.

Degrave E, Meeusen B, Grivegnee AR, Boniol M and Autier P (2009) Causes of death among Belgian professional military radar operators: A 37-year retrospective cohort study. Int J Cancer 124: 945-951.

Frey A (1971) Biological function as influenced by low power modulated RF energy. IEEE Trans Microw Theory Tech 19: 153-164.

Goldsmith JR (1997) Epidemiologic evidence relevant to radar (microwave) effects. Environ Health Perspect 105 (Suppl 6): 15-79-1587.

IARC (2013) Non-ionizing Radiation, Part 2. Radiofrequency electromagnetic Fields: IARC Monographs on the Evaluation of Carcinogenic Effects to Humans. World Health Organization Publication 102.

NTP (2016) Report of partial findings from the National Toxicology Program carcinogenesis studies of cell phone radiofrequency radiation in Hsd Sprague-Dawley SD rats (whole body exposure). https://biorxiv.org/content/bioxiv/earlt//2016/06/23/055699_full.pdf.ley SD rats (whole body exposure).

Panagopoulos DJ, Lituvsky R, and Chamberlin K (2026) Recording the extremely low frequency pulsations of wireless communication electromagnetic fields. Electromag Biol Med 1-10. https://doi.org/10.1080/15368.2026.2654072.

Peleg M, Berry EM, Deitch M, Nativ O and Richter E (2023) On radar and radio exposure and cancers in the military settings. Environ Res 216: 114610.

Rea WI, Pan Y, Fenyves EI, et al. (1991) Electromagnetic field sensitivity. J Bioelectricity 10: 241-256.