Effects of Microwave Radiation on Human Brain: The Positives and Negatives

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Abstract—Several RF sources are present for the commercial as well as defense application. In this article we will focus on the neurological consequences of Microwave Radiation (MWR). Since microwaves impact so many facets of our lives, this research focuses on their health implications. The brain is perhaps the most sensitive organ to MWR, with mitochondrial damage manifesting faster and more profoundly than in other regions. The effects of MWR on brain metabolic pathways have piqued public attention. The possibility for significant numbers of people to be subjected to dynamic, multi-frequency microwave energy nowadays, is a reality. Many urban people residing in the high-rise structures of the city, come in the main beam radiation of the antenna which is mounted at a comparable height. Owing to the pervasive presence of MWR, its extensive usage, and the potential for harmful effects, comprehensive analyses of the health risks are imperative. It is crucial, therefore, to assess the level of exposure that is safe for the general population so as to minimize adverse effects despite reducing the favorable uses of microwaves.

Keywords— EM spectrum, Radiation, Microwave, Neurological hazards

I. INTRODUCTION

The electromagnetic (EM) spectrum, as we all know, encompasses all kinds of EM radiation. Radiation is a form of energy that flows and disperses as it does so. EM radiation can take many types, including visible light from a lamp in your home or radio waves from a radio station. The EM spectrum starts all the way from DC, 3 kHz, it goes to a few THz. From the application point of view, at extremely low frequencies of the spectrum, the sources are, basically earth and subways. After that, the power outlets: 50 Hz AC capacity in India and 60 Hz in the USA, find its place in the EM spectrum. Next comes AM FM radio; AM radio frequency is from 530 to 1620 KHz and then FM radio which ranges from 88 MHz to 108 MHz, followed by TV transmission [1]. Beyond that, microwaves work at 2.45 GHz including Wi-Fi, which works from 2.4 to 2.483 GHz. EM radiations are classified into 2 zones- one is known as a nonionizing zone, and another is known as an ionizing zone. There's far more energy in ionizing radiation, given by the formula $E = hf$, where f is frequency. So, the higher the frequency, the higher the energy would be. So, it can sever the molecular bond and is thus referred to as ionizing radiation. The microwave frequency, essentially has a lower frequency and therefore, has lower energy. Energy, however, is not only defined by $E = hf$; energy also equals power multiplied by time. Therefore, if power is greater, less time will be needed and if the power is lower, the task can take longer to do. In order to focus on the detrimental effects of MWR, let us consider an instance. There are AM towers where the standard frequency range is from 530 to 1620 KHz and these AM towers can transmit approximately, 100

KW of power up to even 1 MW of power. The telecommunication authorities, however, take care and there is at least no residential building or complex within a 1 km radius. They know, therefore, that such actions cause a health hazard, and therefore they take that precaution. Microwave devices, on the other hand, operates between 300MHz to 300GHz. There are airports, railway stations, universities, schools and numerous Wi-Fi-enabled facilities. Also, there are plans to build cities with Wi-Fi. This, in fact, can also create a lot of health issues for several individuals. Several technologies in India operate in 800MHz-band including CDMA, GSM at 900MHz, then GSM at 1800MHz, then we have 3G and 4G. 3G-operators in India are allowed to transmit 20 W of power. An additional concession is given to a 4G operators; they can transmit up to 40 W of power and consequently there are more than 6 lakh towers in India.

II. SPECIFIC ABSORPTION RATE AND ITS IMPACT

A. Specific Absorption Rate

Let us consider a case where it goes to the nearest base station where a mobile phone propagates 1 W of power and that base station actually transmits 20 W of power to communicate with this same cell phone. Then, via a switching network, this base station (say, BS1). In fact, the Specific Absorption Rate (SAR) value of the cell phone determines the radiation from the cell phone. Its limit has been set at 1.6 W/kg. However, the threshold was set in 1998 and this threshold was set at only 6 minutes per day use. So, the mobile phones that people use were originally planned for just 6 minutes of daily usage, communicates with some other base station (BS2), which transmits another 20 W of power to the cell phone, which transmits 1 W of power. So, for one mobile phone connection $1 + 20 + 20 + 1 = 42$ W of power has been consumed. Surprisingly, the effective power used by cell phones as well as cell towers is only 0.0000001 W, which means, 41.99999 W power is getting dissipated in the atmosphere. When a call is initiated, roughly one-third of the power is getting absorbed in the human body; specially if the cell phone is held erect against the ears, then one-third of the power is going towards the head. But as far as the cell towers are concerned, it affects people living in direct proximity.

B. Effects of SAR

The dose of the absorbed energy is measured in terms of Specific Absorption Rate (SAR), expressed in watts per kilogram (W/kg) of body weight. In fact, the SAR value of the cell phone determines the radiation from the device. In 1998, the limit (safety threshold) of SAR has been set at 1.6 W/kg which translates into daily use of cell phone for only 6 minutes. So, the mobile phones that people use were originally planned for just 6 minutes of daily usage. By virtue of a safety margin of 3 to 4 times, a person should not use cell phone for more than 18 to 24 minutes per day. Thus, the lower the SAR value the better it would be. The typical SAR value may vary from 0.3 W/kg to about 1.6 W/kg. Depending on the holding posture, there are chances that 90% of the radiation is going towards human body. It is of utmost importance to reduce the exposure to Radio Frequency (RF) energy. The RF electromagnetic fields have been classified as potential carcinogen (class 2B) in the factsheet released by the International Agency for Research on Cancer

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(IARC) [2], [3]. Scientists are recently, persuading WHO to make this scenario as class 2A which is known as probable carcinogen or even class 1, which is known human carcinogen [4]. Based on several epidemiological studies reporting about the incidence of leukaemia in children and brain tumours in adults after prolonged exposure to Magnetic Field (MF) of approximately, 0.4 μ T, it has been speculated for many years that both residential and industrial exposures to extremely low frequency (ELF) MF may be a potential carcinogen. The carcinogenic potential of cellular communication systems has been determined to be limited to glioma [5].

III. POSITIVE ASPECTS OF MICROWAVE RADIATION

A. Microwave Ablation Technique

The charge switches signs almost 2 billion times a second (9.2×10^8 Hz) in a microwave oscillating at 9.2×10^8 Hz. As a radiation-induced oscillating electric charge interacts with a water molecule, the molecule flips. To optimise this interaction, microwave radiation is tuned to the natural frequency of water molecules. The electrical charge on the water molecule flips back and forth 2–5 billion times a second as a result of the microwave energy impacting the molecules, depending on the frequency of the energy. The vigorous motion of water molecules enhances the temperature of water. Temperature is an indicator of how quickly molecules move in a medium.

Microwave ablation (MWA) is yet another minimally invasive cancer procedure. Ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI) are all used by MWA to guide the placement of a specialised needle-like probe through a tumour. MWA uses microwaves to heat and dissolve tumours. MWA is a low-risk procedure with a shorter hospital stay for the patient. Many tumours may be treated by ablation at the same time. When a new cancer develops, the treatment should be replicated. It is necessary to use a straight needle. The MW generator produces EM waves in the MW energy spectrum. It is bound to the needles by insulated wires. In certain patients with liver cancers that are unsuitable for surgical resection, MWA may be a successful therapy for primary liver cancer and cancers that have metastasized to liver. Similar argument is applicable to lung tumors. This therapy of MWA can be extended to the treatment of brain tumours as well. More than half of liver tumours treated with ablation have not recurred in most studies. Tiny liver tumours can be entirely removed with a success rate of more than 85%. Significant treatment-related complications are uncommon, and the trauma is less than that of surgery. Ablation can be used to combat chronic liver cancers on a regular basis. There is no need for a surgical incision—only a slight nick in the skin that does not require stitches. The amount of tumour tissue that can be removed by ablation is limited. This is due to current equipment constraints.

B. Detection of Brain Strokes using Microwave Tomography (MWT)

In developed countries, cerebrovascular injuries (CVAs) are one of the leading causes of physical disability and mortality in adults. Ischemic or cerebral infarction (85% of cases) and hemorrhagic CVAs (or strokes) are the two forms of CVAs (or strokes) (15 percent). The extent of the stroke must be determined. In order to implement the appropriate treatment, it must be assessed quickly. Strokes induce alterations in the dynamic electric permittivity of brain tissues, which can be detected using microwave tomography, according to recent research in biomedical imaging. MRI or CT imaging are now the only ways to distinguish the type of stroke. However, these cumbersome and costly frameworks necessitate too much infrastructure to be used outside of the hospital. A microwave imaging system with 24 antennas was created recently [6] for evaluating an algorithm based on the Truncated Singular Value Decomposition scheme [7], and a previous analysis on 2-D phantoms used the linear sampling approach for brain stroke monitoring [7]. In the microwave frequency spectrum, recent studies have shown that complex permittivity is dependent on the type of stroke (ischemic or hemorrhagic). Indeed, complex

dielectric permittivity increases by up to 20% in the hemorrhagic stroke region [8], whereas it decreases by 10% in the ischemic stroke area [8], [9]. Because of their intrinsic contrast mechanism, low cost, and short acquisition time, microwave imaging techniques are quite a promising form of stroke classification [10]. EMTensor GmbH (Vienna, Austria) has developed a compact microwave scanner for stroke detection and management [11], which can be integrated into ambulances. MWT could present a better, portable and cost-effective alternative to existing imaging techniques for non-invasive examination of acute and chronic functional and pathological problems of soft tissues. MWT was stunted for a variety of technological reasons, including the high prices of specialized hardware modules and an inadequate processing capacity. Huge progress has been made in recent years. Over recent years, remarkable advancements in both communication technology (mobile) and computation have launched unique possibilities for MWT research and innovation in clinical and therapeutic applications. Biological tissues are distinguished in the microwave spectrum and can thus be imaged based on their dielectric properties. The safety aspect of MWT imaging is crucial. In comparison to CT imaging and nuclear medicine, which use ionising radiation, this modality uses a non-ionizing electromagnetic (EM) field. Applications of MWT includes: radiology of the extremities, breast cancer screening, lung cancer diagnostics, brain imaging, and cardiac imaging. It was discovered in the 1980s and 1990s that malignant tumours and healthy tissues possess different dielectric properties [12]–[15]. This principle is used in identifying the stroke area by MWT.

IV. NEGATIVE ASPECTS OF MICROWAVE RADIATION

A. Related Articles on Brain Dysfunction

In the present article, various studies reporting the effects of MWR on the brain (especially the hippocampus) have been scrutinized. The present article has focused on recent advances in this arena and encompasses the reviews of epidemiology, anatomy, electroencephalograms, learning and memory capabilities and the dynamics substantive to cognitive impairments. In broadcasting, the applications of microwaves are primarily TV broadcasting antennae and FM radio, that emit frequencies ranging between 80 and 800 MHz. Microwaves are created in telecommunications as a result of the proliferation of mobile phones and their associated base stations and microwave links. Microwaves are found in cordless phones, terrestrial trunked radios, blue-tooth services, and wireless local area networks (LANs). Various experiments have been undertaken to examine the effect of electronic networking technologies on humans, but only a few have identified a statistical correlation between cell phones and brain tumours. Those that are used to using a mobile phone ipsilaterally have a two-fold elevated chance of developing brain tumours relative to those who do not [16]–[18]. In a particular study group examining the risk of glioma and acoustic neuroma according to age at first exposure to mobile phones, the highest odds ratios was found among those first exposed before age 20 years [19]. Many other studies haven't yet endorsed the inference that brain tumors can be caused from mobile phone usage [20]–[24]. Yet another study conducted by the Interphone study group [25] concluded that the risk of malignant tumours like glioma or meningioma in mobile phone users did not increase. Gliomas are not present in the most exposed regions of the brain, according to new research by Larjabaara et al. [26]. There were 347 cases of melanoma in the head and neck region, as well as 1184 controls, in this study. Hardell et al. [27] analyzed the usage of cell and cordless phones and observed no significant risk. Dasdag et al. [28] examined personnel working at a TV transmitting station with a frequency spectrum of 202–209 MHz, 694–701 MHz, 750–757 MHz, or 774–781 MHz and medium-band broadcast station. Questionnaires on their health conditions were issued to the workers. The latter showed that symptoms including stress, fatigue, headaches and sleeplessness were experienced. To maintain vital functions, the brain needs a high supply of oxygen and energy intake. As a consequence, non-harmful stimuli such as

ionising radiation and hypoxia can impair this organ [29], [30]. MWR destroys hippocampal structures in rats, impaired cognitive potentiation, lowers neurotransmitter concentrations, decreases the amount of synaptic vesicles, and causes memory impairment, according to certain research communities [31]. The long-term risks from radiofrequency radiation (RFR) exposure from mobile phones appears to be high in children owing to their rapid growth rates and greater vulnerability of nervous system. The increasing use of mobile phones in children, a form of addictive behaviour, has been associated with emotional and behavioural disorders [32]. In a study involving 13,000 mothers and children, it was found that prenatal exposure to mobile phones was associated with behavioural problems and hyperactivity in children. [33] In a Danish study involving 24,499 children, the emotional and behavioural difficulties at age of 11 years among children was noted to be higher (23% increased Odds) in children whose mothers reported any mobile phone use at age 7 years compared with children whose mothers reported no use of mobile phones at age of 7 years. [34] A recent cross-sectional multicentric (20 study sites) study in US involving 4,524 children aged 8-11 years indicates that shorter screen time and longer sleep periods independently improves cognitive function. [35] Another recent study also indicates about the potential adverse effect of RFR on adolescents' cognitive functions. Interestingly, this impairment of cognitive function includes the spatial memory related to the brain regions which are exposed during mobile phone use. [36] Exposures to various non-thermal microwave EMF can adversely affect with diverse neuropsychiatric problems including depression. [37] In a comprehensive literature review, Pall ML states that "Wi-Fi causes oxidative stress, sperm/testicular damage, neuropsychiatric effects including EEG changes, apoptosis [cell death], cellular DNA damage, endocrine changes, and calcium overload,". [38] Furthermore, these effects from continuous, long-term exposure may be cumulative, and that pulsed signals are more biologically active than a smooth carrier wave. Different study have reported variable effect of exposure to RF-EMF in the vicinity of short-wave broadcast transmitter on the sleep parameters ranging from prevalence of difficulties in the initiation and maintenance of sleep [39] to no effect [40]. Studies evaluating sleep quality among humans exposed to extremely low frequency electromagnetic field (ELF-EMF) have not reached to any conclusive evidence [41]. A recent study conforms with the lack of overall effects on sleep architecture, well-being, cognitive function and clinically considerable effects on sleep by RF-EMF similar to those emitted by 3G mobile phones [42], [43]. However, in the same study a reduction of sigma-1 power spectrum was observed which might have implications on long-term sleep quality. [44] Contradictory outcomes have been reported in literature owing to methodological limitations and hence no final conclusions can be drawn about the potential effect of microwaves on sleep. Brain deterioration and structural damage are two of the detrimental effects of MWR on the brain. According to an epidemiological review, MWR induces human exhaustion, headaches, excitement, dreams, memory loss, and other neurasthenia symptoms [45]. A cross-sectional study designed to detect neurobehavioural disorders among the residents living in the vicinity of base stations and are exposed to radiofrequency-electromagnetic field (RF-EMF) found that the prevalence of neuropsychiatric complaints such as memory problems, headache, sleep disturbances, depressive attitude, dizziness etc were considerably more among the exposed individuals compared with the controls. [46] In a cross-sectional community-based study in Singapore involving people using hand-held mobile phone, headache was found to be the most prevalent central nervous system symptoms compared with the nonusers; the prevalence of headache increased further with increased duration of usage per day. [47] Several studies have identified a correlation between exposure to ELF-EMFs and the onset of Alzheimer's disease [48], [49] though their physiological nexuses are uncertain. One speculation is RF-EMF induced biochemical modifications, oxidative stress and ROS generation which is involved mainly in neurodegenerative disorders such as Alzheimer disease, Huntington disease, and Parkinson disease. This can also be associated with induction of several neuropsychiatric

disorders, including anxiety disorders, depression, impairment of emotional and mental well-being [50], [51].

B. Adverse effects of MWR on neurological activity: Mechanism of Action

The adverse effects of electromagnetic field (EMF) are assumed to be indirect effects of several biochemical modifications. Thermal and Nonthermal interactions, oxidative stress, decrease in melatonin secretion, disturbances in calcium ion efflux/influx and thereby influencing cAMP pathway and serotonin/melatonin conversion and their efflux from the cells of pineal gland—are some of the proposed mechanisms. [52] The interaction with NADH oxidase in the plasma membrane leads to formation of reactive oxygen species (ROS) which activate the matrix metalloproteinases. This causes activation of ERK cascade (one of the four mitogen-activated protein kinase signalling cascades) which adversely affects the cell cycle progression, apoptosis, differentiation and metabolism in a complex manner. [53] Among all, the oxidative stress and ROS generation appears to be the most important mechanism for damage to DNA, protein and lipids [54]. The brain shows high metabolic rate and high oxygen intake but has poor energy stores. The brain has the highest need for oxygen in the human body and hence it is vulnerable to any disruptions in energy metabolism owing to ionizing radiation and hypoxia. It is said that the nervous system is practically helpless to ROS insults owing to its high metabolic rate, inadequate oxidant protection and reduced cellular turnover. [54] The primary site for Oxidative Phosphorylation and Adenosine Triphosphate (ATP) synthesis is mitochondria. The respiratory chain's redox enzymes and coenzymes are found in close proximity to the inner mitochondrial membrane. Mitochondria play a variety of roles in the body, including apoptosis regulation and Ca^{2+} storage, in addition to energy conversion. Mitochondria are both the initiating point and the target of several signaling pathways. Neurons are intrinsically very responsive to a decrease in ATP supply. Mitochondria, as the body's primary source of energy, are vulnerable to MWR damage. Succinate De-Hydrogenase (SDH) is one of the most important enzymes of mitochondrial energy metabolism. In animal model, the activity of SDH in rat hippocampus has shown to be decreased dramatically at 6 hours after radiation, culminating in alterations of mitochondrial energy metabolism. The terminal complex of mitochondrial electron transport chain, the Cytochrome c OXidase (COX), is embedded in the inner membrane of mitochondria [55]–[57]. COX activity has been reportedly inhibited by certain levels of MWR. The findings revealed that MWR has toxic effects on COX activity compounded over time and that there was a dose-dependent correlation [56]. A mutation in the gene encoding the enzyme Copper-Zinc $\text{Cu}^{2+}/\text{Zn}^{2+}$ Superoxide dismutase (SOD) can alter the function of this antioxidant. This mutation (SOD1) has been found in about 20% of patients of Amyotrophic Lateral Sclerosis (ALS), a neurodegenerative condition that causes motor neurons in the spinal cord, motor cortex, and brainstem to degenerate progressively [58]. MWR alters the expression of genes that code for the respiratory chain, resulting in problems with brain energy metabolism. MWR has the potential to increase molecular rotation and vibration, as well as the frequency of collisions between molecules, causing chemical bonds to break and thus damage the mitochondrial membrane [59]. Secondly, MWR causes oxidative modification of biological macromolecules and mitochondrial damage by increasing intracellular reactive oxidative species (ROS) and disrupting antioxidant enzymes, resulting in oxidative modification of biological macromolecules and mitochondrial damage. Similar to X-rays, the exposure to microwave radiation can generate reactive oxygen species (ROS) [60]–[63]. Additionally, MWR activates phospholipases and proteases, which triggers intracellular Ca^{2+} overload and mitochondrial membrane damage [64]–[67]. MWR induced brain damage involves the phosphatidylinositol 3-kinase (PI3K)/Akt pathway. This is a pro-survival anti-apoptotic kinase signaling cascade which plays an important role for cellular survival [68], [69]. Akt is a serine/threonine protein kinase, also known as protein kinase B (PKB). This Akt is the primary

protein effector situated downstream of the PI3K signalling pathway. Akt plays an important role in glucose metabolism by regulating the biological function of insulin [70]. Dysregulated PI3K/Akt pathway has been linked or incriminated with various carcinogenesis [71]. MWR can alter the expression or can cause structural damage of mitochondrial DNA. This results in decreased ATP production [72]. In animal model, exposure to microwaves resulted in excessive activation of N-methyl-D-aspartate (NMDA) receptor signalling pathway. Thus the microwaves adversely affect the learning process and memory by modulating the hippocampal synaptic plasticity. Maternal exposure to microwaves may lead to numerous neurological effects in the baby [73]. Table I summarizes the degrading effects of prolonged exposure to MWR.

V. CONCLUSION

In this field of study, considering the negative effects of MWR, the following problems are present: (a) The dosage, duration, and frequency of MWR-induced disruption of brain energy metabolism are all variables that need to be investigated further; (b) The long-term consequences of MW radiation-induced mitochondrial damage are unknown, and its connection to mitochondria-related neurodegenerative (ND) disorders like Alzheimer's disease warrants further investigation. The lack of uniform standards among laboratories creates a barrier to further growth and knowledge sharing. Many ND disorders, such as Parkinson's disease (PD), Alzheimer's disease (AD), Huntington's disease (HD), and Amyotrophic Lateral Sclerosis (ALS), are caused by ND mechanisms, and many of them are known as pathologies because of protein aggregation. Several reports seem to point to a connection between MWR exposure and occupational health but it still requires more conclusive results.

On the positive side, several technological advancements will possibly allow for the treatment of larger tumours in the future using MWA. Ablation is as yet, incapable of destroying microscopic tumours or preventing cancer from recurring. In this article, we have also focused on microwave imaging to diagnose and identify strokes. The advantage of the hemorrhage's physical properties can be utilised. It includes a 10% improvement in permittivity on both real and imaginary components. Thus, in many aspects MWR proves to be very beneficial for life.

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TABLE I
ADVERSE EFFECTS OF MWR

Researchers	Dosage of MWR	Results
Xie et al. [55], [79]	Exposed male Wistar rats, MWR (3 and 30 mW/cm ² for 1 h)	<ol style="list-style-type: none"> 1) Damaged mitochondria in the 30 mW/cm² group, rest unaffected. 2) Ultrastructural changes in the mitochondria were induced within 24 h post MWR exposure. 3) Post MWR of 30 mW/cm² for 0, 3 and 24 h, decreased COX I mRNA expression in the rat cerebral cortex and hippocampus.
Xiong et al. [56]	MWR of 30 mW/cm ² on male Wistar rats	Decreased COX activity and Reduced expression of COX I/IV mRNA and COX I protein were found.
Zhao et al. [57]	Exposed male Wistar rats, MWR (30 mW/cm ² , duration: 5 min)	Mitochondrial ATP content in the hippocampus dropped to the lowest levels 3 d post MWR and recovered by next 7 d.
Wang et al. [60]	Exposed monkeys, MWR (95 mW/cm ² and 11 mW/cm ² for 10 s and 4.68 μ W/cm ² for 12 h/d for 30 d cumulatively)	Abnormalities in mitochondrial function-related metabolites in urine.
Zhao et al. [61]	Exposed male Wistar rats, MWR (2.5, 5 and 10 mW/cm ² , with SAR of 1.05, 2.1 and 4.2 W/kg, respectively, for 6 min/d for 30 d)	Mitochondria were swollen and vacuolized with ultrastructural changes due to the increasing SAR.
Kesari et al. [74]	Exposed 45-day-old male Wistar rats, 2 h/d for 60 d by mobile phone (3G)	<ol style="list-style-type: none"> 1) Induced DNA strand breaks in the brain. 2) MWR induced apoptosis in the brain by activation of p38MAPK, the pathway of principal stress response.
Xu et al. [75]	Exposed cortical neurons of neonatal rats to MWR	Expression of mtTFA mRNA and protein increased.
Lu et al. [76]	Exposed primary cultures of glial cells to 2450 MHz MWR (4 mW/cm ² for 2 h/d for 3 d)	An increased intracellular free Ca ²⁺ was found.
Wang et al. [77]	Exposed Wistar rats, MWR (10, 30 and 100 mW/cm ² for 5 min, respectively)	Reduced SDH activity which recovered 7 d post MWR.
Sander et al. [78]	Exposed SD rats, MWR with a frequency of 591 MHz (13.8 mW/cm ²)	Reduced availability of ATP, resulting in brain energy metabolism disorders.
Dong et al. [80]	Exposed SD rats, MWR (4.68 μ W/cm ² , 12 h/d, duration: 30 d)	Swelling and cavitation in the mitochondria hippocampus and cerebral cortex.

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