The Microwave Auditory Effect

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Abstract—**The microwave auditory effect has been widely recognized as one of the most interesting and significant biological phenomena from microwave exposure. The hearing of pulsed microwaves is a unique exception to sound waves encountered in human auditory perception. The hearing of microwave pulses involves electromagnetic waves. This paper reviews the research in humans and animals leading to scientific documentations that absorption of a single microwave pulse impinging on the head may be perceived as an acoustic zip, click, or knocking sound. A train of microwave pulses may be sensed as buzz, chirp, or tune by humans. It describes neurophysiological, psychophysical, and behavioral observations from laboratory studies involving humans and animals. Mechanistic studies show that the microwave pulse, upon absorption by tissues in the head, launches a pressure wave that travels by bone conduction to the inner ear, where it activates the cochlear receptors via the same process involved for normal sound hearing. Depending on the impinging microwave pulse powers, the level of induced sound pressure could be considerably above the threshold of auditory perception to cause tissue injury. The microwave auditory effects and associated pressures could potentially render damage to brain tissue to cause lethal or nonlethal injuries.**

Index Terms—**Animal and human study, audible microwave, brain response, health and safety risk, microwave hearing, microwave pulse technology, transduction mechanism.**

I. INTRODUCTION

THE microwave auditory effect pertains to the hearing of pulse-modulated microwave energy at high peak power by humans and laboratory animals [1]–[3]. It has been widely recognized as one of the most interesting and significant biological phenomena from microwave exposure [4]–[7]. The hearing of pulsed microwaves or audible microwaves is a unique exception to the sound energy, normally encountered in human auditory perception. The hearing apparatus commonly responds to airborne or bone-conducted acoustic or sound pressure waves in the audible frequency range (up to 20 kHz). But the hearing of microwave pulses involves electromagnetic waves whose frequency ranges from 100's MHz to several GHz. Since electromagnetic waves (e.g., light) are commonly seen or visible, but not heard or audible, the report of auditory perception of microwave pulses was at once astonishing and intriguing. Moreover, it stands in sharp contrast to the responses associated with continuous-wave microwave radiation.

This paper describes the research studies in humans and animals leading to scientifically documenting that the absorption of a single microwave pulse impinging on the head may be perceived as an acoustic zip, click, or knocking sound. Depending on the incident power and pulse width, a train of microwave pulses to the head may be sensed as a buzz, chirp, or tune by humans. The review present what is scientifically known about the microwave auditory effect and associated pressure waves. It discusses behavioral, neurophysiological, psychophysical, and mechanistic studies involving humans and laboratory animals as subjects.

Studies have shown that the microwave auditory phenomenon does not arise from an interaction of microwave pulses directly with the central auditory nervous system. Instead, the microwave pulse, upon absorption by soft tissues in the head, launches an acoustic pressure wave that travels by bone conduction to the inner ear. The traveling wave activates the cochlear receptor cells via the same process involved for normal sound hearing. The pressure waves induced by high power microwave pulses could be considerably above the threshold of auditory perception. The microwave-induced pressures that exceed levels of discomfort could potentially produce enough damage to brain tissues to cause lethal or nonlethal injuries in animals and humans.

II. A HISTORICAL PERSPECTIVE

The earliest reports of the auditory perception of microwave pulses were provided anecdotally by airmen and radar operators during World War II and shortly thereafter. In particular, the Airborne Instruments Laboratory [8] described in an advertisement, observations made in 1947 on human auditory detection of microwave signals at radar installations. Others had passed on their experiences with microwave auditory effect to their physicians, journalists, or magazine editors. The witnesses described an audible sound, often as a zip, click, or buzz that occurred at the pulse repetition frequency (PRF) of radars when standing in the radiation beam of radar antennas. A decade later, the information gathered by interviewing people who had experienced the auditory sensation was evaluated and collated with radar transmitters in a technical note [1]. The report provided clues to the effect's characteristics.

The note found in field experiments that radar transmitter frequencies from 200 MHz to 3000 MHz had elicited auditory responses from subjects who were over 100 ft away from the radome enclosing the transmitter's antenna. Subjects blindfolded with tight-fitting blackened goggles reported perception which coincided perfectly with pulsed microwave exposure. When earplugs were used to attenuate the ambient noise, the subjects indicated an apparent increase in the level of microwave-induced sound. Moreover, in a paired test, it was found that persons shielded from the impinging microwave

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radiation ceased to report perception. Subjects who were not shielded continued to report hearing microwave-induced sonic signals. The sensations occurred instantaneously and appeared to originate from within or behind the head; the orientation of the subject in the microwave field was not an important factor. Another finding was that subjects who were asked to compare the perceived sound with conventional sound invariably chose their parallels from the higher frequencies and eliminated frequencies below 5 kHz. The report showed that the human auditory system can respond to pulse-modulated RF and microwave radiation and referred to this auditory phenomenon as "RF sound." The report conceded that in classic physiology the auditory and visual systems are distinguished by the "fact" that the two systems respond to different types of energy, acoustic and electromagnetic, respectively; however, the report contended that it had obtained data which suggested that "this fact may not be correct."

The earlier observations were extended to a wider range of microwave frequencies (200 MHz to 8.9 GHz, but with no auditory response at 8.9 GHz) during the following two years [9]–[11]. These papers contained much of the same field tests results given in the 1961 paper [1]. They also reported that people with a notch in their audiogram around 5 kHz may have difficulty perceiving microwave-induced sound. The stated objective of the 1962 paper [10] was to bring the phenomenon to the attention of physiologists and likewise, the 1963 paper [11] was to acquaint clinicians with the phenomena. These papers mentioned that with appropriate modulation, the perception of various sounds can be induced by microwave pulses in human subjects at inches and up to thousands of feet from the radar transmitter. It suggested that further experimental work with these phenomena may yield information on auditory system function and, more generally, information on nervous system function. It discussed some preliminary studies into evidence for the various possible neurophysiological sites of microwave or electromagnetic "sensors" and had specifically ruled out locations peripheral to the cochlea, such as the middle ear. Indeed, a region over the temporal brain lobe was favored as a sensitive area for detecting the microwave auditory effect. This assertion was repeated in a later publication [12]. It was mentioned that the data suggested the microwave auditory effect was neuronal in nature and possibly involving direct interactions with the auditory nerve, central auditory nervous system, and the auditory cortex, which is incorrect, as shown by current scientific understanding.

There were two other reports from that same year [13], [14]. One of them reported sensation of 1–2 μs wide microwave pulses at 6500 MHz [13]. The findings in this descriptive paper echoed those of the other papers by saying that, albeit with very little support, the microwave auditory effect takes place by direct stimulation of the nervous system, perhaps in the brain, bypassing the ear and the associated auditory system. In any case, the reports were met with skepticism and the hearing sensation from radars was dismissed by most scientists as an artifact. Perhaps because the studies were conducted as field tests at radar installations with limited control measures, which raised questions that could not be answered then. However, beginning in the early 1970's, the situation started to change.

The psychophysical technique of magnitude estimation was used in a controlled laboratory experiment to study the perception of sound induced by pulse-modulated microwave radiation inside a microwave anechoic chamber [15]. A pulse microwave power source generated amplitude modulated carrier signals at 1245 MHz. The PRF was selected so that it produced a buzzing sound. Human subjects with clinically normal hearing were tested individually within the microwave anechoic chamber. The test subjects sat on a wooden stool with their backs to a horn antenna. The subject indicated sound perception with a hand switch. The data suggested that the perception of microwave-induced sound was primarily a function of the peak power density and secondarily dependent on pulse width. The report also indicated that a band of optimal pulse widths seems to exist for the microwave auditory sensation. It speculated that the perception did not involve transduction of electromagnetic to acoustic energy. It further suggested that the perception differed from the electrophonic effect and could not be accounted for by an explanation involving radiation pressure against the body surface. However, the data reported from this experiment was received as consistent and reliable. It served to affirm previous field reports of microwave auditory effect and helped to facilitate documentation of the phenomenon of microwave auditory effect. The apparent reliability of the data had encouraged other investigators to embark on further psychophysical experiments in attempts to confirm the observations. In a sense, this report [15] served as a water-shed moment opening the door for the microwave auditory effect to be accepted as a scientific fact, following further controlled laboratory investigations by others.

One investigation commenced using a 2450-MHz laboratory microwave source capable of providing up to 10-kW peak power pulses with pulse width varying from 0.5 to 32 μs [2], [16], [17]. Pulsed microwave energy was launched through a S-band aperture horn antenna. Microwave absorbing materials were placed around the vicinity of the subject to minimize microwave reflections. The horn antenna, absorbing material, and test subject were situated in a shielded room completely isolated from the power generating equipment and experimenter to eliminate disturbing noises and unwanted subject-experimenter interactions. The subjects sat with the back of the head directly in front of the horn antenna and used a light switch to signal the experimenter when an auditory sensation was perceived. The investigation found that each individual pulse could be heard as a distinct zip or click originating from somewhere within or near the back of the head. Short pulse trains could be heard as chirps with the tune corresponding to PRF. When the pulse generator was keyed manually, transmitted digital codes could be accurately interpreted by the subject. It is significant to note that the energy required for auditory perception by a subject with normal hearing was approximately a third to a quarter of that required for a subject with sensorineural conduction hearing impairment.

Another laboratory experiment followed up on the microwave induced auditory sensation in humans [18], [19]. The subject's head was places under a horn antenna which delivered 15- or 20-μs pulses of 3000 MHz radiation. The study applied the same psychophysical protocols mentioned above. The subjects (n = 5) reported hearing a click, originating from inside the head. Although there were some variations in hearing acuity, none of the subjects had a pronounced hearing loss greater than 25 dB. This study also hinted at the possibility that microwave-induced sound in humans may contain a significant portion of its energy above 8 kHz.

These controlled laboratory studies [2], [15]–[19] confirmed the earlier field reports and, they demonstrated that humans can indeed consistently hear pulsed microwave radiation. An auditory sensation is perceived when the head is exposed to 200 to 6500 MHz pulse-modulated microwave energy with a peak power density in the range of 1 to 10 kW/m^2 and pulse widths from 1 to 100 μs. The microwave-induced sound appears as an audible zip, click, or knocking sound, and as buzz, hiss, or chirp depending on such factors as pulse width and PRF of the impinging microwave radiation. The auditory sensation is always perceived as originating from within or behind the head. When the pulses are delivered manually, transmitted digital codes could be reliably interpreted by human subjects. While these investigations helped microwave auditory effect to become accepted as a real phenomenon, the specific neurophysiological site or anatomical location of transduction and the mechanism of microwave auditory effect remained obscure for some time. Nevertheless, the microwave auditory effect had evolved into a major topic of scientific research; the substance of which will be discussed in the following sections.

III. THRESHOLD POWER AND LOUDNESS FOR HUMAN PERCEPTION

Since the first report that pulse-modulated microwave radiation induces an auditory sensation in the human, several investigators have attempted to assess the thresholds for sensation as a function of microwave parameters. The microwave-induced sound depends on such exposure factors as pulse width, peak power, and the PRF of the impinging microwave radiation. The average power does not significantly impact microwave auditory effect.

A. Field Tests of Adult Humans with Normal Hearing

Plane-wave exposure in the far zone of radar antennas was involved in the early field experiments. The ambient noise level was about 70 dB and earplugs that attenuated tunes between 125 Hz and 8000 Hz by 25 to 30 dB were used. The peak power density perception threshold for eight subjects was 2.67 kW/m^2 for 6-μs wide, 1310-MHz microwaves pulsed at 244 Hz [1]. For the 2982-MHz (1-μs pulses at 400 Hz) experiment, the ambient noise level was 80 dB. Earplugs were used. The peak incident power density threshold for seven subjects was 50 kW/m^2. The determination of threshold power density for perception was extended to 425 MHz in another reported field experiment involving various microwave parameters [10]. The measured ambient sound level was 70–90 dB. The report also provided field tests made at 216- and 1310-MHz. All field measurements were summarized in a later publication [11], including an average threshold of 2.54 kW/m^2 at 425 MHz for pulse widths of 125 μs to 1000 μs (see Table I). Note that with earplugs in place, the ambient noise levels likely are in the range of 45 to 50 dB for these plane-wave power density thresholds.

TABLE I
THRESHOLD POWER DENSITY FOR HUMAN AUDITORY PERCEPTION OF PULSED MICROWAVES IN FAR FIELDS

Ambient Noise Level 70 to 90 dB (with Earplugs 45 to 60 dB)				
Frequency	Pulse Width	Peak Power Density	Pulse Rate	Duty Factor
MHz	μs	kW/m^2	Hz	
216	---	6.70	---	.006
425	1000	2.54	27	.028
425	500	2.29	27	.014
425	250	2.71	27	.0007
425	125	2.63	27	.00038
425	---	2.54 (Ave)*	27	---
1310	6	2.67	244	.0015
2982	1	52.50	400	.0004

TABLE II
THRESHOLDS OF AUDITORY SENSATION IN ADULT HUMANS WITH NORMAL HEARING IN LABORATORY STUDIES

Frequency	Pulse Width	Peak Power Density	Ambient Noise Level	Study
(MHz)	(μs)	(kW/m^2)	(dB)	Ref.
1245	10-70	0.9 - 6.3	45*	[15]
2450	1-32	12.5-400	45	[2, 17]
3000	10-15	2.25-20	45**	[18]
Pulse Width Between 10 and 32 μs				
1245	10-30	2.1 - 6.3	45*	[15]
2450	10-32	12.5-40	45	[2, 17]
3000	10-15	2.25-20	45**	[18]

*Typical SPL for microwave anechoic chambers lined with absorbing materials; ** With plastic foam earmuffs.

B. Laboratory Study of Adult Humans With Normal Hearing

The threshold peak power density for adult humans was investigated under controlled laboratory experimental conditions at frequencies of 1245, 2450, and 3000 MHz with pulse widths of 1–70 μs. In contrast to the plane-wave field experiments, these studies involved near-zone exposure of the subjects. The results of these efforts to establish the threshold of microwave-induced auditory sensation are given Table II.

Also, the thresholds for auditory perception of pulsed RF energy absorption in the human head have been studied for six subjects with magnetic resonance imaging (MRI) head surface coils [27]. RF exposure frequencies ranged from 2.4 MHz to 170 MHz and pulse widths varied from 3 ms to 100 ms. Apart from the different frequency range explored, the use of MRI coils also provides a different mode of RF power deposition which is predominantly of an inductive nature via the interaction of RF magnetic field with lossy dielectric tissues of the head. The auditory effect RF energy thresholds were observed at 16 mJ per pulse. The auditory threshold of RF pulse widths greater than 200 ms occurred at an average peak power level as low as

20 W for surface coils. The study noted that the results are in excellent agreement with data from horn antenna measurements at 2450 MHz [2], [16], [17], using the assumption of an effective head absorption area of 400 cm^2 for conversion of reported peak power density data into absorbed peak power levels in the head.

In one study, adult subjects with clinically normal hearing were tested individually in a microwave anechoic chamber with a sound pressure level of 45 dB [15]. The method of magnitude estimation was used. A buzzing sound was perceived by the subjects. It was found that the threshold peak power densities required for perception are functions of both pulse width and peak power. The threshold values ranged from 0.9 to 6.3 kW/m^2 which varied inversely with pulse widths from 10 to 70 μs with average power and energy per pulse kept constant.

The psychophysical method of limits or minimal change was the experimental protocol and conditions associated with another study [2], [16], [17]. The near-zone 2450-MHz exposure was conducted in a microwave anechoic chamber with a 45 dB ambient sound pressure level. The data suggest that the threshold for a 2450 MHz microwave-induced sound is related to both pulse width and peak power for average power densities of 1.2 W/m^2 and energy densities of 400 mJ/m^2 per pulse of 1- to 32-μs width pulses.

The threshold of microwave auditory sensation in humans at higher frequency radar installations was assessed in a laboratory with a noise level less than 45 dB [19]. Five subjects with normal audiograms reported hearing clicks in response to 10- and 15-μs wide 3000 MHz microwave pulses delivered through a horn antenna. Threshold incident peak power density and energy per pulse were obtained individually for the five subjects [18]. Although there are similarities, the thresholds differed among subjects and were different for 10- and 15-μs pulses; the average threshold incident peak power densities are 13.25 and 5 kW/m^2, respectively. Note that the subjects showed some variations in hearing acuity, even though they were deemed having normal hearing by audiograms. Some had appreciable amount of hearing loss for frequencies higher than 8 kHz.

Table II presents a summary of the thresholds determined under controlled laboratory conditions for peak microwave power density of auditory perception in human subjects with normal hearing. Note that while there are variations in measured threshold values over the entire range of 1 to 70 μs of pulse widths involved, the subset of data for 10 to 32 μs fall within a narrower range. Considering that the ambient noise in all three experiments was about the same, it is rational to conclude that the threshold power densities of 2.25 to 40 kW/m^2 or an average quantity of 13.86 kW/m^2 are a realistic threshold peak power density for induction of the microwave auditory effect.

C. Loudness of Human Perception

In general, a sensory response such as perceived loudness of sound is inversely proportional to threshold of sensation. The loudness of perception as a function of pulse width for human subjects exposed to pulse-modulated 800 MHz microwave radiation was determined in 18 male and female subjects with normal high-frequency auditory acuity [26]. A 500 W source was coupled through a coaxial cable to a waveguide, which was mounted on a plastic rest that permitted transmission of microwaves to the parietal area of a subject's head. The pulses were 5 to 150 μs wide, and the PRF varied from 50 Hz to 20 kHz at constant power. The loudness for sensation at 8000 Hz is shown in Fig. 1(plotted from data provided in [26]). As the width of pulses of constant peak power density were gradually increased from 5 to 150 μs, a complex oscillatory loudness function was observed. The loudness increased as pulse width increased from 5 to 50 μs, then diminished with further increase of pulse width from 70 to 100 μs, and then increased again with longer pulse widths. It is significant to note that in this meticulously conducted experiment, the head of the subjects is at various levels above the water line with the rest of the body submerged in a large steel drum containing seawater. By pressing a switch, the subject informs the researcher sound detection when a microwave pulse or an acoustic stimulus is presented, or a shift in loudness has occurred. These experimental results corroborated earlier theoretical predictions based on a spherical model of the head [22]–[25]. The character of the loudness curve is consistent with the predictions (see section VI for further discussions). They are also in agreement with results obtained at different microwave frequencies by other investigators [2], [15]–[17].

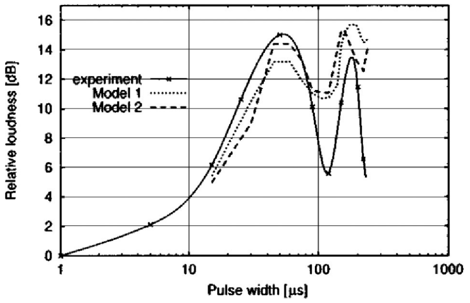

Fig. 1. Loudness of pulse induced sound level as a function of microwave pulse width in human subjects [60].

IV. BEHAVIORAL STUDY IN ANIMALS

The previous section demonstrated that under certain conditions humans can perceive pulse-modulated microwaves as sound. Because the auditory perception involved a discrimination response to differential characteristics of impinging pulsed microwaves, a common issue in studies involving human subjects – the possibility of subjective responses, is averted by using animals. Furthermore, confirmatory evidence in lower animals can substantially enhance the observation of microwave-induced auditory sensation as a genuine biological response.

A. Discriminative Control of Appetitive Behavior

That microwave pulses are acoustically perceptible and can serve as a discriminatory auditory cue in behavioral experiments is reported in a discriminative control of appetitive behavior by pulse-modulated microwave energy in rats [28]. The aim of this investigation was to substitute pulse-modulated microwave

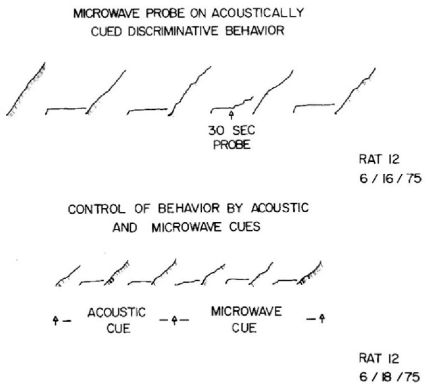

Fig. 2. Cumulative record showing an animal's performance. Top: In response to 30-s microwave probe, rat begins to respond as if acoustic cue had been presented. Bottom: Rat responds equally well during presentation of acoustic and microwave stimulation [28].

for the previously well-discriminated tune cue (acoustic click). The subjects were six female white rats (300 to 350 g Wistar-derived strain). The animals were partially deprived of food until their body mass fell to 80% of that before deprivation. They were then placed in a body-movement restrainer and trained to perform a head-raising response for food pellets. During daily 90-min sessions, individual rats were presented alternating 5-min stimulus-on/stimulus-off periods during which food was made available as a reward for responding only during stimulus-on periods. The initial stimulus was a 7.5 kHz acoustic click produced by a high frequency speaker driven by a 1-volt, 3-μs wide rectangular pulse at the rate of 10 Hz. After these animals learned to show evidence of their responses so that 85 to 90% of a given session's total responses were made during the appropriate stimulus-on periods, individual animals were then exposed to 30 s of pulse-modulated 918 MHz microwaves at the same pulse width and PRF as the acoustic stimuli at average incident power densities up to 50 W/m^2. These animals began to respond immediately (Fig. 2). In subsequent sessions when microwave, not the acoustic click, was present during the stimulus-on periods, the rat responded equally well during presentation of acoustic and microwave stimulation [28]–[30]. This result clearly suggested an auditory component in the microwave control of this behavior.

B. *Pulsed Microwave as a Cue in Avoidance Conditioning*

The detection and use of pulsed microwaves as a cue in avoidance conditioning in animals have been reported over the years [31]–[34]. Sprague Dawley rats (male, 150 g, 125-day-old) were tested in a microwave anechoic chamber which contained two acrylic barrier boxes [35], [36] to determine whether rats would perceive pulse-modulated microwave energy and respond to it behaviorally. Each box consisted of two compartments. The compartment of the right of one box was shielded, and for the other, the one on the left was shielded from the impinging microwaves using microwave absorbers to minimize microwave exposure of the respective sides of the boxes and to exclude any possible effect due to side preference. The location of the subject was monitored using a switch affixed to the bottom of each compartment of the barrier box. Rectangular microwave pulses (30-μs wide, 1245 MHz) were derived from a pulse source at the rate of 100 Hz and were fed to a horn antenna. The incident power density at 5 cm above the floor of each half of the boxes, when the animal was absent, was measured using a half-wave dipole. The average power densities in the unshielded compartment were 10 W/m^2. The shielded side had a value of 7% or less of the unshielded side. After acclimation to the barrier boxes, place-avoidance conditioning was initiated with pulse-modulated microwaves as the discriminative stimuli. During each 90-min session, cumulative measurements of residence time in shielded and in unshielded compartments was taken to reflect the course and status of conditioning. Control sessions were run with all equipment turned on but without power output. The number of crossings was reduced substantially in the experimental group over the entire experimental sessions. The animals did not exhibit a preference between the compartments in the absence of microwaves (control group). Rats exposed to 1.33 or 3.0 kW/m^2 peak power density exhibited an avoidance of the unshielded compartment or spent most of their time in the shielded side. The observance of avoidance behavior in the absence of explicit location cues led the investigators to conclude that the rats could perceive pulse-modulated microwave radiation.

Another investigation of microwave-induced auditory sensation tested rats in a shuttle-box experiment, in which one compartment was exposed to 33 kW/m^2 of 2880-MHz microwave pulses at 100 Hz with a pulse width of 3 μs and the other was shielded. Cumulative measurements of residence time in shielded and in unshielded compartments were taken to reflect the status of conditioning. Rats were found to spend significantly more time in the shielded side [37]. When a high-frequency (37.5-kHz tune) acoustic stimulus was exchanged for the microwave pulses, rats exhibited a preference for the acoustically "quiet" side. In addition, the amount of side-to-side traversing activity was greater in rats exposed either to microwave pulses or acoustic stimuli in both sides of the box than in unexposed control animals. It suggests that rats find the pulsed microwave to be aversive and are motivated to actively avoid it. The simultaneous presentation of a broad band acoustic noise (20 to 40 kHz) and pulsed microwaves produce no statistically significant differences of side preference between experimental and control groups. In contrast, in all cases the number of traverses made by microwave exposed rats were significantly greater than those of unexposed controlled rats. These results indicate that pulse microwave stimulus and the acoustic tune stimuli can result in similar behavior patterns and support the notion that rats acoustically detected the microwave pulses and generalized the microwave induced sound and conventional acoustic cues.

V. NEUROPHYSIOLOGICAL STUDY IN ANIMALS

Behavioral studies rely on inference rather than direct measurement of the anatomic or physiologic entities involved in microwave pulse interaction with the auditory system. Therefore, they need to be complemented by direct observations in identifying the responsible anatomic or physiologic substrates.

On many sites such as the cerebral cortex, thalamus, cranial nerve, and cochlea associated with the mammalian auditory sensory pathway, small electrodes may be attached, implanted, or inserted to record the electrical potentials arising in response to acoustic stimulation. If the electrical potentials elicited by microwave pulses exhibited characteristics akin to those elicited by conventional acoustic pulses, this would rigorously support the behavioral findings that pulsed microwaves are acoustically perceptible. Direct and quantitative experimental findings that are related to these characteristics will further the understanding of pulsed microwave interactions with the auditory system. They may confirm or refute hypotheses about direct neural excitation. If microwave-evoked potentials are recorded from the inner ear, this would lend support to the contention that microwave auditory effect is mediated distally at the periphery, outside the cochlea, as is the case of a conventional acoustic stimulation.

Microwave induced auditory response has been described in reports from several laboratories in terms of recordability from the peripheral and central nervous systems of laboratory animals and similarity between microwave evoked electrical potentials and those produced by conventional acoustic stimuli. Indeed, there are several different types of electrical activity which may be recorded from the inner ear and the brain during pulse stimulation. These interesting studies designed to help establish the site of interaction and the mechanism involved in the pulsed microwave-induced auditory sensation are discussed in this section, together with experimental observations on the electrophysiological events that occur along the auditory sensory pathways in response to pulsed microwave exposure and purposeful manipulations, including tissue ablation, along the auditory pathway. The discussion begins with the simplest method without any need of surgical procedures - brainstem evoked electrical potential recording via a surface or scalp electrode affixed to the vertex on top of the head.

A. Brainstem Evoked Response

When acoustic pulses or clicks are presented through loudspeakers to a human or animal subject, a characteristic sequence of evoked electrical potentials - brainstem evoked response (BER) can be recorded via surface or scalp electrodes [38], [39], [40]. The BER responses show a series of early components that occur during the first 8 ms following the onset of a stimulus that represents activation of the cochlea and the auditory brainstem nuclei. The BER potentials are highly repeatable from one subject to the next and reflect brain activity from cochlea to the auditory cortex. These complex electrical potentials are therefore of importance in the objective evaluation of hearing.

Several investigators have reported BER responses recorded from the vertex of laboratory animal's head using surface electrodes [41]–[46]. The BER potentials evoked by microwave and acoustic pulses from the vertex of a cat are shown in Fig. 3.

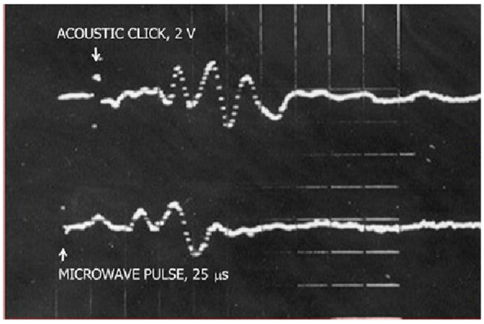

Fig. 3. Brainstem electrical potential responses (BER) from the vertex of a cat's head evoked by acoustic clicks and microwave pulses [45].

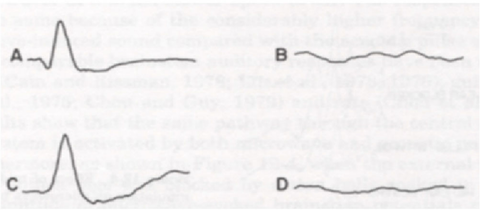

Fig. 4. Primary cortical responses in the cat to acoustic clicks and microwave pulses: A and C are response signals before bilateral destruction of the cochlea. Disablement of both cochlea in the animal resulted in total loss of the responses in the cat to acoustic click (B) and pulsed microwave (D) stimulation [48].

Note the comparable response characteristics. Furthermore, microwave pulse evoked responses are seen immediately after delivery of the pulse, without the familiar acoustic wave propagation delay. These results show that the same pathway through the central nervous system is activated by both microwave and acoustic pulses. Clearly, microwave energy does not need to be deposited in the cochlea to initiate the microwave auditory effect.

B. Primary Auditory Cortex

A series of studies recorded the auditory responses in the primary auditory cortex of anesthetized cats irradiated by pulsed microwaves [2], [16], [17], [48]. Each cat was fitted with a piezoelectric crystal transducer for the presentation of acoustic stimuli via bone conduction. Following surgical observation of the auditory cortex, a microwave-transparent carbon electrode was then placed, under direct visualization, on the surface of the anterior ectosylvian gyrus. The microwave stimuli of rectangular 2450 MHz pulses were fed to a horn antenna. Fig. 4A and 4C show typical evoked responses recorded from the auditory cortex following pulsed microwave and conventional acoustic stimulation. Note the remarkable similarity between these responses. Also, the surgical maneuvers permitted both round windows to be clearly visualized. When responses were clearly established, the cochlea was disabled by perforation of the round window. Aspiration of the contralateral cochlea led to marked reduction of the amplitude of the evoked potentials. Disablement of the other cochlea resulted in total loss of the response signal, as shown in Fig. 4B and 4D. These results showed that the same pathway through the central nervous system is activated by both microwave and acoustic pulses. Furthermore, the cochlea has an essential role in the auditory perception of pulsed microwaves.

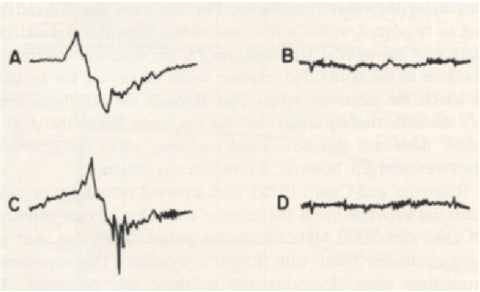

Fig. 5. Acoustic and microwave pulse-evoked respones recorded from the medial geniculate body of a cat. A and C are the corresponding response signals before bilateral destruction of the cochlea. Total loss of the medial geniculate responses in the cat to acoustic click (B) and pulsed microwave (D) stimulation following perforation of both cochlea in the animal [48].

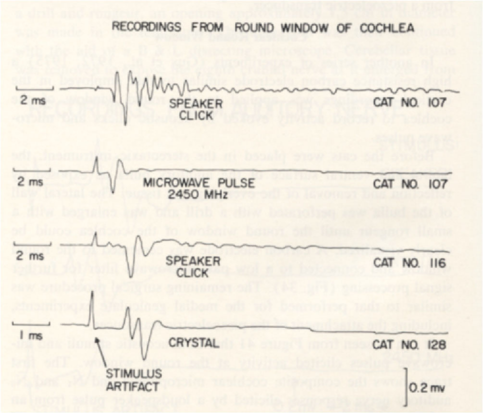

Fig. 6. Carbon electrode recordings from the round window of the cat cochlea elicited by acoustic click and microwave pulse stimuli [2].

C. Central Auditory Nuclei

Electrophysiological signals have been recorded, by using a glass microelectrode filled with Ringer's solution, from the medial geniculate body of cats exposed to 918- and 2450-MHz pulses [2], [16], [17], [47], [48]. Because the dielectric properties of Ringer's solution and brain tissues are similar, the glass pipettes filled with Ringer's solution were essentially transparent to microwaves when used for recording bioelectric signals from the depth of the brain. Following unveiling of the dorsal surface of the skull, a burr hole was made in the parietal bone. An electrode was directed toward the medial geniculate body by the standard stereotaxic method. Fig. 5A and 5C present typical evoked responses recorded from the medial geniculate body due to acoustic and 2450 MHz microwave pulse stimulation. The similarities between the responses are evident. Other investigators also reported similar activities from the medial geniculate nucleus [44], [45], [49]. Note that damages to the cochlea led to total loss of the medial geniculate body's responses to both acoustic and microwave stimuli (Fig. 5B and 5D).

Using the same procedures, responses from the medial geniculate of the cat were reported for pulses of microwaves between 8670- and 9160-MHz [2], [17]. The required microwave power to elicit the responses was higher than those for lower frequencies. The X-band horn had to be placed within a few cm from the exposed brain surface (through the 1.0 cm electrode access hole in the skull). Responses was not elicited for an animal in which the electrode access port was limited to slightly larger than the electrode. However, when the hole was enlarged and baring the soft brain tissues, a response was observed. Thus, deposition of microwave power in soft tissues in the head was necessary for microwave-induced auditory sensation.

In addition to the medial geniculate, the experimental procedures just described including glass microelectrodes filled with Ringer's solution were used to investigate microwave pulse-induced auditory response from the inferior colliculus of cats [18], [19]. Recordings of evoked electrical activities were obtained from the inferior colliculus of cats exposed to 10-μs wide 3000-MHz microwave pulses. It was also found that the evoked potentials in response to acoustic and pulsed microwave stimuli disappeared in these animals following replacement of the antenna with a dummy load and following death.

Using a small direct-contact 2450-MHz antenna, microwave pulse-evoked auditory responses have been recorded from the medial geniculate, inferior colliculus, lateral lemniscus, superior olivary nuclei, and the vertex of cats [44]–[46]. Microwave-evoked responses were seen immediately following delivery of stimulus, without the familiar transmission delay associated conventional acoustic waves traveling through air. These recordings indicated that brainstem nuclei potentials can be evoked by microwave pulses and that they have characteristics that closely resemble those evoked by conventional acoustic stimuli.

An earlier study had implanted coaxial metal electrodes in the brainstem of cats [12]. Because of the similarity of the acoustic and microwave evoked activities, and because the responses were seen immediately before but not immediately after death, it was assumed that the signals were neural rather than an artifact of the experimental protocol. It was suggested that the effect might be the result of direct stimulation of the auditory nervous system at a site central to sound perception. It was also based on failure to observe any cochlear microphonics associated with pulsed microwaves in cats and guinea pigs [12], [33], even with incident power densities far above those needed to induce the microwave auditory effect in cats. However, caution must be taken in accepting these assumptions [12], [33], because the exposure protocol and microwave fields induced on the metal recording electrode [47], [50].

D. The Eighth Cranial Auditory Nerve

Auditory nerve responses were obtained in cats placed in the head holder described previously [2], [16], [17], [47], [48]. Following surgical removal of the cerebellar tissues to reveal the eighth cranial nerve as it emerged from the internal auditory meatus, a Ringer's solution filled glass microelectrode was inserted within the nerve. The response to loudspeaker showed a classic propagation delay between stimulus and response. Similarly, the microwave-induced activity is like that evoked by an acoustic click from a piezoelectric transducer that launched the acoustic sound signal via bone conduction to the cochlea. Unilateral ablation of the auditory nerve led to total loss of these evoked potentials both to acoustic and microwave stimuli.

Note that recordings from single auditory neurons in the cat also demonstrated a response to microwave pulses that was akin to acoustic stimuli. Neural responses to 915-MHz microwave pulses were studied by recording extracellular action potentials of individual neurons in the eighth cranial nerve and in the cochlear nucleus with glass microelectrodes. Post-stimulus time histograms of the auditory (eighth) nerve fibers and cochlear nucleus units showed that time-locked microwave responses depend monotonically on pulse amplitude but nonmonotonically on pulse width [51]–[53]. The results of single unit studies not only support a microwave-anatomic interaction site at or peripheral to the cochlea, but also showed consistency with the thermoelastic theory discussed later. The study also indicated that auditory units with lower characteristic frequencies (a few kHz) to be more responsive to microwave pulses than were units with higher characteristic frequencies.

E. Cochlear Round Window and Microphonics

The role of the cochlea in microwave-induced auditory phenomena has been discounted in earlier reports, based on not observing a microphonic in either cats or guinea pigs [12], [33]. In a series of studies [2], [16], [17], [47], the lateral and ventral surfaces of the auditory bulla in cats were surgically revealed, and the lateral wall of the bulla was perforated to clearly visualize the round window of the cochlea. A carbon electrode was cemented to the round window to record activity evoked by acoustic clicks and microwave pulses (Fig. 6). The top trace shows the composite cochlear microphonics and N_1 and N_2 auditory nerve responses from an animal elicited by a loudspeaker. A robust cochlear microphonic is exhibited. When the auditory system of the same cat was stimulated by microwave pulses, a microwave artifact pulse and clear N_1 and N_2 auditory nerve responses were elicited, but there was no evidence of a cochlear microphonic (second trace). However, in some studies, the cochlear microphonic is considerably reduced (third trace) or not present at all (fourth trace) when the cat's auditory system is stimulated by an acoustic click. Several factors could prevent the observance of a cochlear microphonic, especially at low-stimulus intensity. Failure to observe a microwave-induced cochlear microphonics in experimental animals appears to have been due to limitations of the output of the microwave pulse generator or a large microwave-pulse-artifact which concealed the cochlear microphonics.

Further experimentations have successfully demonstrated the existence of microwave-induced cochlear microphonics in laboratory animals with clearly visible acoustically evoked cochlear microphonics by alleviating the difficulties [5], [49], [54], [55]; for example, screening the animals based on whether the cochlear microphonics were evoked by an acoustic click. If positive, the guinea pigs were exposed to 918 MHz microwave pulses (1 to 10 μs) for 90-s intervals at a PRF of 100 Hz and at peak powers up to 10 kW. Fig. 7 illustrates the evoked potentials recorded from the round window of a guinea pig. The responses due to single acoustic clicks from a loudspeaker driven at 10 kHz consisted of a cochlear microphonic which preceded the N_1 and N_2 auditory nerve responses (Fig. 7A). The polarity of the cochlear microphonic changed with a change in the polarity of the electrical energy driving the loudspeaker (Fig. 7A), confirming the authenticity of the observed cochlear microphonics. When the same guinea pig was exposed to pulsed microwave, in addition to the well-defined N_1 and N_2 nerve responses, a high frequency (50 kHz) oscillation was seen preceding and immediately following the microwave stimulus artifact (Fig. 7B). Clearly, cochlear microphonics like that evoked by acoustic stimuli can be induced by microwave pulses. Following death of the animal, whether by anoxia or by drug overdose, microwave-evoked nerve responses disappeared before the cochlea microphonic.

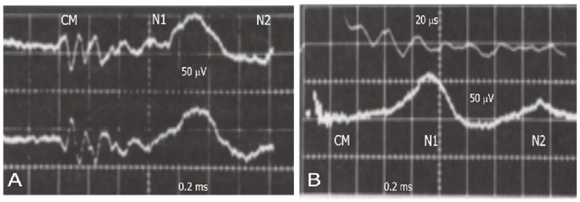

Fig. 7. Cochlear microphonics recorded from round window of the guinea pig. (A upper) Acoustic click stimulus; (A lower) Single 10-μs wide, 918 MHz microwave pulse; (B) time expansion of initial 200 μs microwave [54].

F. Brainstem Nuclei Ablations on Evoked Auditory Responses

Systematic studies of responses from brainstem nuclei: the inferior colliculus (IC), lateral lemniscus (LL), and superior olivary (SO) nuclei, following successive coagulative ablations of loci in the central auditory nuclei have been reported [44], [45]. They provide further support for the findings that microwave-induced auditory sensation is detected by the animal in a manner like conventional sound and help to ascertain that the anatomic site of conversion from microwave to sonic energy resides peripheral or distal to the cochlea. Note that disablement of the cochlea has been shown to eliminate the cortical and medial geniculate body responses (Figs. 4 and 5).

Brainstem lesions at the electrode tips were successively made in the IC, LL, and SO nuclei. After each lesion, a new set of responses was recorded from the vertex and from each of the depth electrodes and were compared to those obtained prior to lesion. Decreased amplitudes recorded from each of the electrode sites with successive lesion production in IC, LL, and SO nuclei were readily observed. For an example of the responses recorded at the vertex see Fig. 3, which is clearly a function of the integrity of auditory brainstem nuclei. Fig. 8 shows decreased amplitudes recorded from the electrode at the proximal IC site with successive lesion production in the IC, LL, and SO nuclei. The reduction in amplitude is most pronounced for IC following lesion production in it. Note also the severe loss of IC responses following LL and SO ablation.

A second example is given in Fig. 8, where the effect of brainstem ablative lesions on signals recorded from the distal SO nucleus in response to microwave pulse stimulation is shown.

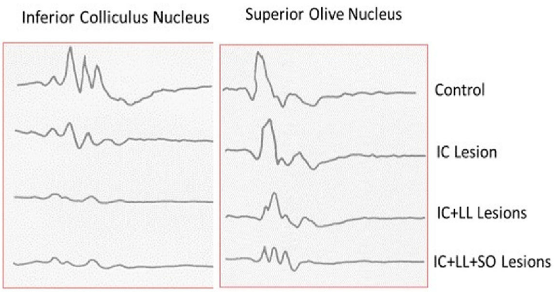

Fig. 8. Effect of successive brainstem ablative lesions on electrical potentials from the inferior colliculus (control) and superior olive nuclei (control) evoked by 25-μs wide, 2450 MHz microwave pulses in the cat: Inferior colliculus (IC), lateral lemniscus (LL), superior olive (SO) nuclei [45].

Lesions in the more proximal IC and LL nuclei had minimal impact on the response recorded from the SO nucleus. However, the response was vastly reduced after lesion of the SO nucleus; thus, confirming again the peripheral nature of the primary site of transduction.

G. *Manipulation of Middle and Outer Ears on BER Potentials*

Investigations have shown that when the external auditory meatus of guinea pigs was blocked by cotton balls soaked in mineral oil, the microwave evoked BER potentials remained unaltered. Similarly, filling the middle ear cavity with mineral oil, which impeded ossicular movement, had minimal effect on microwave evoked response. In addition, disablement of both tympanic membrane and middle ear ossicles led only to a slight reduced brainstem potential [41], [48]. These findings indicate that the external and middle ears are not the route used by microwave-induced sound. They suggest that the interaction of pulsed microwaves with the auditory system is not mediated by any air-borne sound reception mechanism. In addition, the studies described above demonstrated that ablation of the central auditory nuclei and damage to the cochlea in the cat resulted in total loss of the acoustic and microwave pulse induced responses. These results suggest that the same pathway through the central nervous system is activated both by microwave and acoustic pulses. The cochlea plays an essential role in the auditory perception of pulsed microwaves. And the site of initial sound detection is inside the cochlea, but it is not the initial or primary site of microwave-to-acoustic energy conversion. An observation supported by the finding that the microwave auditory effect in humans is independent of head orientation in the pulsed microwave field.

H. *Brain Tissue as Site of Interaction*

A peripheral or distal anatomic site of primary interaction should involve displacement of the tissues in the head with resultant dynamic consequence in the cochlear fluids and neural correlates that have been well subscribed for the acoustic case. Indeed, cochlear microphonics, the signature of mechanical modification of neural hair cells inside the cochlea have been observed in response to microwave pulse stimulation. These results clearly implicate the mode of interaction and energy conversion for pulse-induced microwave auditory effect as electromechanical in nature and it does not involve the middle ear apparatus or the cochlear apparatus. Thus, the anatomic site of initial interaction is peripheral and distal to the cochlea and is in brain matters or soft tissues of the head.

The participation of brain matters has been demonstrated in laboratory studies through visualization of functional brain activity associated glucose utilization [56]. Autoradiography involving $^{[14C]}$2-deoxy-D glucose was used to map in vivo auditory metabolic activity in the brain of rats exposed to acoustic clicks and microwave pulses. Prior to exposure one middle ear was destroyed to block sound transmission in one side. Asymmetry of radioactive tracer uptake was observed in the central auditory nuclei of rats exposed to acoustic clicks. In contrast, a symmetrical uptake of tracer was found in the auditory nuclei of brains exposed to microwave pulses. Aside from confirming that the microwave auditory effect does not require an intact middle ear, the autoradiography authenticates the involvement of brain tissues in the microwave response.

VI. MECHANISM OF INTERACTION

The thermoelastic theory has been shown as the most effective mechanism since pressures generated by thermoelastic stress are two to three orders of magnitude greater than by any other proposed mechanisms [3], [4], [6], [7].

The microwave auditory effect occurs from the miniscule but rapid increase of temperature in brain tissue from absorption of pulsed microwave radiation. This sudden rise of theoretically tiny temperature (on the order of 10^{-6} °C for a 10-μs pulse) is practically unmeasurable with currently available instruments. But it can create thermoelastic expansion of the brain matter, which then launches a stress or pressure wave that travels through the tissue structures in the head to reach the cochlea where it is detected by the sensory hair cells in the cochlea. The neural signals are then relayed to the central auditory system for perception and recognition at the cerebral auditory cortex.

The first mathematical models for analyzing the sound pressure waves inside the head due to a microwave pulse used a homogeneous spherical model of the head [22]–[25] by assuming a spherically symmetric specific absorption rate (SAR) pattern that peaked at the sphere center. The same analytic method was later applied with a slightly modified SAR pattern which included a uniform SAR offset [58]. A generalization of the methodology, again using a homogeneous sphere head model but with an arbitrary SAR pattern of spherical symmetry, has also been reported [59]. More precise computer simulations of the properties of microwave-pulse-induced sound pressure wave using realistic anatomic head models have also been conducted [7], [58], [60]–[62].

These multidisciplinary analyses of the thermoelastic pressure wave generated in spherical and anatomical human heads exposed to pulsed microwave radiation showed that the attributes of thermoelastic sound pressure closely resemble those reported for humans. The theory predicted a remarkable nonlinear sound pressure behavior (Fig. 1). It initially increases with pulse width,

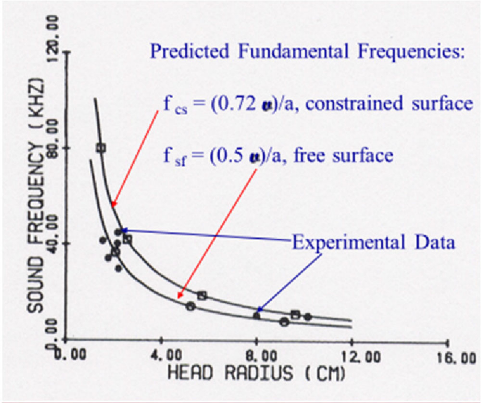

Fig. 9. Theory predicted and experimental measured audible range of frequencies as functions of the subject's head size [4].

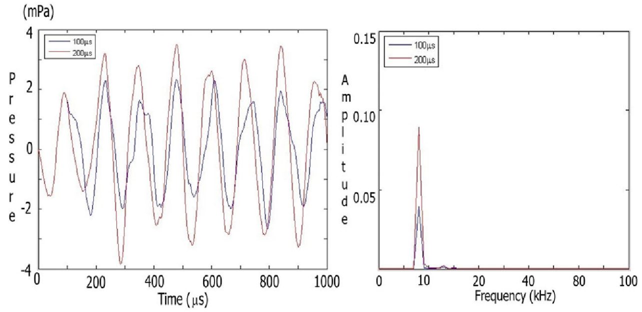

Fig. 10. Computed pressure waves (Left) and amplitude spectra (Right) for an anatomic head model of adult human exposed to 400 MHz microwave pulses of 200-μs (Red) and 100-μs (Blue) width [61].

after reaching a peak value with further increases in pulse width, it starts to oscillate toward a lower pressure [22] - [25]. The results showed remarkable similarity to the variation of loudness perception with pulse width in human subjects exposed to microwave pulses [4], [7], [26].

In addition, the thermoelastic theory predicted a fundamental sound frequency that varies inversely with head size: the smaller the radius, the higher the frequency. Fig. 9 compares the predicted and measured sound frequencies for cats, rats, guinea pigs, and humans. For rats, it predicted acoustic frequencies of 25 to 35 kHz in the ultrasonic range, which rats can easily hear. For human heads, the theory predicted frequencies between 7 and 15 kHz, which are clearly within the audible range of humans. A time series of computer-simulated microwave pulse-induced pressure wave is given in Fig. 10. Initially, a negative pressure is noted to begin at zero, then grow to a peak value, and is followed by oscillations, which could rise to even higher peaks, after the end of the pulse [7], [61]. The associated amplitude spectra of the pressure waves are also shown in Fig. 10; the spectral amplitudes for the 200-μs pulses are greater than that of the 100-μs pulses. Significantly, a fundamental frequency component at about 8 kHz inside the head was observed both for 100- and 200-μs microwave pulses. These results indicate an acoustic resonance giving rise to a reverberating thermoelastic pressure wave inside the head.

VII. Health and Safety Implications

Since late 2016, there have been multiple reports that some diplomatic service personnel have been experiencing health issues associated with hearing loud buzzing or bursts of sound. It was hypothesized that the loud buzzing, burst of sound, or acoustic pressure waves may have been delivered using a targeted beam of high-power pulsed microwave radiation, rather than blasting the subjects with conventional sonic sources [63], [64]. Recently, the National Academies released a report [65], examining the causes of the illnesses, makes the point that "among the mechanisms the study committee considered, the most plausible mechanism to explain these cases, especially in individuals with distinct early symptoms, appears to be directed, pulsed RF (microwave) energy."

Absorption of a single microwave pulse impinging on the head and conversion of microwave pulse to acoustic pressure wave by soft tissues inside the head may be perceived as an acoustic zip, click, or knocking sound. A train of microwave pulses to the head may be sensed as an audible buzz, tune, or chirp. Depending on the power of the impinging microwave pulses, the level of induced sound pressure could be considerably above the threshold of auditory perception. Indeed, they may approach or exceed levels of discomfort and even tissue injury, including reported headaches, concussion, and problems with balance or vertigo. Furthermore, compared with individuals not experiencing the loud bursts of sound, brain magnetic resonance imaging (MRI) revealed, significant differences in whole-brain white matter volume, regional gray and white matter volumes, cerebellar tissue microstructural integrity, and functional connectivity in the auditory and visuospatial subnetworks but not in the executive control subnetwork [66]. However, the clinical importance of these differences is obscure. A high-power microwave pulse-generated pressure wave could be launched in the brain, reverberate inside the head, and potentially reinforce the initial pressure to cause injury of brain matters.

The near-zone thresholds determined under controlled laboratory conditions for peak microwave power density of auditory perception in human subjects with normal hearing are given in Table II. While there are wide variations in measured threshold values for pulse widths of 1 to 70 μs, the subset of data for 10 to 32 μs fall within a narrower range. The noise levels in these experiments were about the same; it is reasonable to conclude that the threshold power densities of 2.1 to 40 kW/m^2 or 14 kW/m^2 as a median threshold peak power density for induction of microwave auditory effect in the near field of 1250- to 3000-MHz microwaves with pulse widths between 10 and 30 μs. In other words, the 14 kW/m^2 per pulse peak power density generates a barely audible sound level of 0 dB at the cochlea [4]. Generating sound at 60 dB, or the audible level for normal conversation, requires 1000-fold higher power density per pulse. Generating tissue injuring level of sound at 120 dB at the cochlea, would take another 1000-fold increase in required peak power density, or about 14 GW/m^2 per pulse. The corresponding theoretical temperature elevation would be about 1 °C, which is "safe" by current protection guidelines.

For plane-wave equivalent exposures, the computations mentioned provide two sets of data that are suitable for comparison with the above results. In one case, the reported threshold peak incident power density for an anatomic head model is 3 kW/m^2 for 20-μs pulses at 915 MHz [60]. For the other, the threshold is about 50 kW/m^2 for 20-μs pulses at 2450 MHz [62]. The corresponding peak incident power densities at the 120 dB injury level are therefore between 3 and 50 GW/m^2 per pulse, which bracket the 14 GW/m^2 per pulse from the calculations for near-zone exposures. These peak power densities are close to and encompass the 23.8 GW/m^2 value for dielectric breakdown of air. As the dielectric permittivity of all biological and physical materials is greater than that of air, the intrinsic impedance is smaller than that of air. The breakdown peak power density in skin, muscle, or brain tissues, for example would be a factor of 6 to 7 higher or 142 to 166 GW/m^2 for a microwave pulse at 1000 to 3000 MHz. Thus, if the microwave auditory effect is weaponized, it is likely for the microwave pulses to primarily cause auditory pathway nervous tissue injury or damages to brain tissues by reverberating sonic shock waves with a theoretical temperature rise about 1°C. The damage would not be by microwave pulse-induced hyperthermia in the brain, nor by dielectric breakdown of brain, muscle, or skin tissues.

Note that the U.S. government has recently announced a research program to develop a low cost, low weight, small size wearable RF weapon exposure detectors [67]. It acknowledged that, “directed energy weapons, including RF weapons, are a growing threat on the battlefield.” It also suggests that the determinants of RF weapon’s antipersonnel effects are multifactorial and RF injuries may be situation dependent. It envisions that aside from being generally useful for military operations, a wide variety of commercial, industrial, manufacturing, and medical applications in which personnel may be inadvertently exposed.

VIII. SUMMARY

The microwave auditory effect occurs from miniscule but rapid (μs) rise of temperature (10^{-6}°C) in the brain from absorption of pulsed microwave radiation. The sudden rise in temperature creates thermoelastic expansion of the brain matter, which can launch a pressure wave that propagates through the head and is detected by the sensory hair cells in the cochlea. The nerve signal is then relayed to the central auditory system for perception and recognition.

The preceding sections document that an audible sound originates from within the head when human subjects are exposed to pulsed microwave radiation. The auditory detection of pulsed microwaves in laboratory animals has been confirmed both in behavioral and neurophysiological studies. The site of microwave-to-sound conversion is shown to be in the brain tissue. The primary mechanism of interaction is microwave pulse-induced thermoelastic expansion of brain matter.

Depending on the power of the impinging microwave pulses, the levels of induced sound pressure in the brain could be considerably above the threshold of auditory perception, so that they may approach or exceed levels of discomfort and cause brain tissue injury. A high-power microwave pulse-generated acoustic pressure wave initiated in the brain and reverberating inside the head could bolster the initial pressure, causing injury of brain matter. Thus, it is conceivable that the microwave auditory effect or the microwave pulse-induced pressure shock wave inside the head could become a potentially lethal or nonlethal weapon against animals and humans.

The unique character of microwave-induced acoustic wave in biological tissues has prompted the exploration of its potential for application in biomedical imaging [68], [69]. The principle of operation of microwave thermoacoustic tomography (MTT) and some results have been available since the early 1980’s [69], [70]. It was conjectured that the potential contrast advantage of microwave imaging and the resolution advantage of ultrasonic imaging could combine to make MTT imaging of biological tissues a potentially useful dual modality for diagnostic imaging. For example, the wavelength in muscle for microwaves is 17.5 mm at 2450 MHz; for ultrasonic waves, the wavelength is a mere 0.5 mm at 3 MHz. The potential gain in spatial resolution is tremendous for tissue imaging compared with relying on using microwave radiation alone. The research initiated in the 1980’s is being actively pursued in developing MTT imaging for medical diagnosis, especially for early detection of breast cancer. Indeed, currently, MTT is a subject of vigorous research both from a systems development perspective and as a dual imaging modality amenable to greater utility in a wide range of medical application scenarios [71]–[75].

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