# Acoustic Pressures in the Head From Pulsed Microwaves: Can They Explain "Anomalous" Health Incidents?

*Kenneth R. Foster, Yinliang Diao, and C-K. Chou*


©SHUTTERSTOCK.COM/ANDREA DANTI

Formerly an obscure effect of microwave energy in humans, the microwave auditory effect (alternatively known as the Frey effect or microwave hearing, referring to "clicks" or "a buzzing sound" that a person experiences when their head is exposed to microwave pulses) has become an important issue with the development of extremely high-powered pulsed microwave generators in directed-energy weapons (DEWs) programs. Expert groups [1] and some scientists—together

*Kenneth R. Foster (kfoster@seas.upenn.edu) is with the University of Pennsylvania, Philadelphia, PA 19104, USA. Yinliang Diao (diaoyinliang@ieee.org) is with South China Agricultural University, Guangzhou 510642, China. C-K. Chou (ck.chou@ieee.org) is with C-K Chou Consulting, Dublin, CA 94568 USA.*

*Digital Object Identifier 10.1109/MMM.2025.3624334*

with many nonscientists on social media—consider the microwave auditory effect as the underlying mechanism causing the symptoms reported by U.S. officers in Havana and elsewhere starting in about 2016 which are referred to in official sources as "anomalous health incidents" (AHIs) but more popularly as the Havana Syndrome. (Neither AHI nor Havana Syndrome are accepted diagnostic entities; see the insert at the end of this article.)

We first describe the long history of studies on the microwave auditory effect and physical basis for the effect and estimate the magnitude of the acoustic pressures that are generated within the head by high-powered microwave pulses by thermoacoustic (TA) sound generation. Finally, we address the question: Could thermally generated acoustic waves in the head have caused the symptoms reported by the Havana officers? The present focus is on the peak acoustic pressures induced in the head and brain by pulsed microwaves and on estimating likely thresholds for adverse effects on an individual. Most previous studies on the microwave auditory effect were concerned with modeling the pressure transients that echo throughout the head and their perception by the auditory system. The instantaneous acoustic pressure at any point within the head results from the superposition of waves generated or reflected from boundaries within the head. These are conveyed to the cochlea through the skull, eliciting sensations of "buzzes" or "clicks" in an individual, with no direction in space as the apparent source.

## Historical Background

In 1947, the Airborne Instruments Laboratory published an advertisement in the *Proceedings of the IRE* (which later became the *Proceedings of the IEEE*) that described sounds that a person heard at the repetition rate of a radar while standing close to a horn antenna [2]. These individuals encountered skepticism and rather pointed questions about their mental health when they described their experiences to their coworkers.

In 1961, Allan H. Frey, who ran a small consulting and research firm in Pennsylvania, reported the first laboratory studies on the effect [3]. In that and in his subsequent 1962 paper [4], Frey confirmed the effect and measured its threshold in a few subjects but offered no explanation for the phenomenon. He found that the sensations could be prevented when shielding was placed over the temporal region of the head (indicated by the stippled areas in Figure 1).

In 1974, Kenneth R. Foster (one of the present authors) and Edward D. Finch provided a simple explanation for the effect: Pulsed microwaves of the sort that elicited the hearing effect would create audible-level sound transients in a plastic container filled with water [5]. Cooling the water to 4 °C (where the thermal expansion coefficient of water vanishes) abolished the effect, and at lower temperatures (where it changes sign) the polarity of the acoustic waves was likewise reversed. This observation showed that the sound transients were related to the thermal expansion properties of the water.

Starting in the mid-1970s, Arthur W. (Bill) Guy and his students C-K Chou (one of the present authors) and James C. Lin at the University of Washington in Seattle, began an extensive series of experiments that documented the thresholds for human perception of microwave pulses. In 1975, Chou recorded electrophysiological responses from the cochlea (cochlear microphonics) in guinea pigs and cats when their heads were exposed to pulsed microwave energy, showing that the auditory effect resulted from mechanical vibrations of the hair cells in the cochlea [6]. The frequency of the hearing was correlated to the long dimension of the skull of guinea pigs and cats [7]. When the guinea pigs were exposed to pulsed energy from a laser or were stimulated by a piezoelectric crystal in contact with the skull, similar cochlear microphonics were recorded. This result indicated that the cochlear microphonics were due to mechanical vibrations of hair cells in the cochlea, where the sensations of microwave hearing arise [6], [8]. The group worked out the theory of TA sound generation in the head and published numerous papers on the effect, and Lin went on to write two monographs on the subject [9], [10]. By the late 1970s, the effect could be considered to be well understood, although

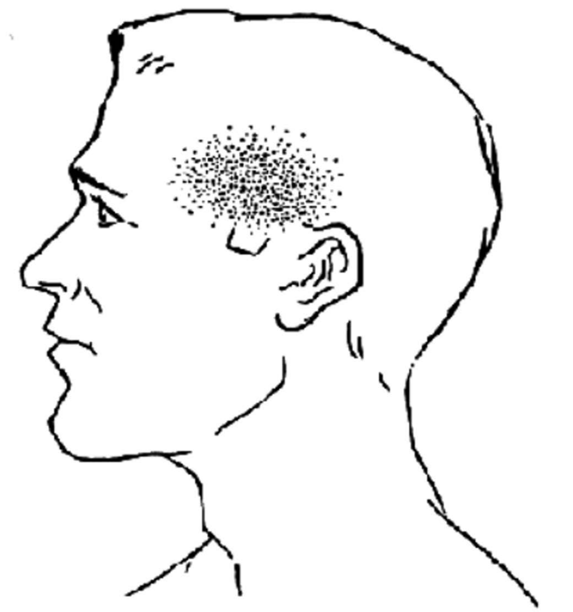


**Figure 1.** *"One can shield, with a 2-in.sq. piece of fly screen, a portion of the stippled area … and completely cutoff the rf sound." (Frey [4]). Reprinted with permission of The American Physiological Society.*

many gaps and needs for additional research were apparent. In 1982, Chou et al. published a paper on this subject in the *Journal of The Acoustical Society of America* as its 80th in a series of review and tutorial papers on various aspects of acoustics [2]. At that time, the microwave auditory effect was a threshold hearing phenomenon, and the pressure transients that could be created within the head by available microwave pulse generators were many orders of magnitude below potentially hazardous levels. That has changed with the advent of high powered (gigawatt) microwave generators.

## Magnitude of Acoustic Pressure Transients Generated by Pulsed Microwaves in the Head

Key to understanding the auditory effect and its potential biological significance requires knowledge of the amplitude of acoustic waves that are induced in the head by exposure to pulsed microwaves. While the theory for TA sound generation is complex because it combines acoustic and electromagnetic wave phenomena, simple expressions can be found for the peak sound pressures induced by brief microwave pulses. The theory of TA sound generation in tissues and liquids is presented in many sources. For a full monograph see Gusev and Karabutov [11]; for reviews of the use of applications of TA pressure generation in biomedical imaging, see Chapter 12 of Wang and Wu's textbook *Biomedical Optics: Principles and Imaging* [12] and Xu and Wang [13].

TA sound generation is characterized by a wave equation

$$\left(\nabla^2 - \frac{1}{v_s^2}\frac{\partial^2}{\partial t^2}\right)p(r,t) = -\frac{\Gamma}{v_s^2}\frac{\partial P}{\partial t} \tag{1}$$

where $v_s$ is the velocity of sound (1,540 m/s in soft tissue), $p(\mathrm{r,t})$ is the acoustic pressure (Pa) at point r and time t, and $P$ is the power deposited by the exposure per unit volume (W/m$^3$). The dimensionless Grüneisen parameter $\Gamma$ is defined as

$$\Gamma = \frac{\beta v_s^2}{C_p} \tag{2}$$

where $\beta$ is the volumetric thermal expansion coefficient of tissue (generally reported to be in the range 3–4 $\times$ $10^{-4}$ K for soft tissue and $C_p$ is the specific heat at constant pressure [3500 J/(kg °C)] [14] which results in $\Gamma \approx 0.2$.

The problem has two characteristic time scales. The first, the stress confinement time, $\tau_s = L/v_s$, where $v_s$ is the velocity of sound in the medium (1,540 m/s), is the time required for acoustic energy to propagate out of the heated region of size $L$. The second and much longer time scale is the thermal confinement time, $\tau_{\mathrm{th}} = L^2/\alpha$, which is the time required for heat to diffuse out of the region, where $\alpha$ is the thermal diffusivity of the medium (about $1.1 \times 10^{-7}$ m$^2$/s for water or tissue). Simple limiting cases discussed next assume short pulses of duration $\tau_p$ such that thermal and stress confinement applies ($\tau_p \ll \tau_s$, $\tau_{\mathrm{th}}$), and simple closed-form solutions to (1) can be found. We consider two ideal cases:

### *Acoustic Waves Produced in a Uniform Tissue by a Microwave Pulse of Incident Intensity $I_o$ and Duration $\tau_p$*

Neglecting reflections of the wave from boundaries and assuming thermal and stress confinement, (1) yields the peak incremental pressure increase $p_{\mathrm{peak}}$ as follows:

$$p_{\mathrm{peak}} = \Gamma \rho \mathrm{SAR} \tau_p \tag{3a}$$

where $\rho$ is the tissue density (1060 kg/m$^3$) and SAR is the specific absorption rate, which is rate of electromagnetic energy deposition per unit mass of the tissue (W/kg). Exposing the head to plane wave microwave energy an incident power density of 1 W/m$^2$ in the frequency range of ≈1–3 GHz results in peak SAR values in the brain of about 0.05 W/kg (see the "Peak Pressure Increases in the Head" section). Consequently, assuming stress confinement applies, at frequencies between 1–3 GHz, (3a) can be simplified to

$$p_{\mathrm{peak}} \approx 11\varphi \tag{3b}$$

where $p_{\mathrm{peak}}$ is in Pascals, and $\varphi$ is the energy density (fluence) incident on the head in J/m$^2$. Expressed in terms of the incremental temperature increase $\Delta T$ and SAR at the same location

$$p_{\mathrm{peak}} \approx \rho C_p \Delta T \tag{4}$$

where

$$\Delta T = \frac{\mathrm{SAR}\tau_p}{C_p} \tag{5}$$

which yields $p_{\mathrm{peak}} \approx 0.8$ Pa/µK for soft tissues. Thus, under conditions of thermal and stress confinement, the incremental temperature and pressure increases from a pulse are proportional to each other and proportional to the fluence of the pulse.

The duration of the acoustic pulse under conditions of stress confinement is determined by the time required for the acoustic wave to leave the region where it was produced and is about $\tau_s$ independent of the microwave pulsewidth. When generated within an enclosed volume such as the head, the acoustic waves will reflect from boundaries and produce a series of echoes at the acoustic resonance frequency of the structure, which for the human head is about 10 kHz. This series of echoes, which persists for about a millisecond, elicits the "buzz" or "clicks" experienced by the subject as they are transmitted to the cochlea through bones in the skull. The auditory sensations are not directional, i.e., do not appear to be coming to the subject from any direction in space.

Equation (3a) can be extended to longer pulses. Ignoring acoustic reflections within the medium, as follows:

$$p_{\text{peak}} = \begin{cases} \Gamma \rho \text{SAR} \tau_p & \tau_p \leq \tau_s \quad (\text{stress confined}) \\ \Gamma \rho \text{SAR} \tau_s & \tau_p > \tau_s \quad (\text{stress unconfined}). \end{cases} \quad (6)$$

Thus, in this simple model, pulses longer than the stress confinement time will be reduced in amplitude compared to equivalent pulses generated under stress confinement by a factor of $\tau_p/\tau_s$.

### *Plane Waves Normally Incident on a Flat Tissue Surface*

Another simple case is for plane waves of power density $I_o$ W/m$^2$ normally incident on a planar tissue surface, where $\rho$ is the tissue density (kg/m$^3$), and $L$ is the 1/e power penetration depth (m) (Table 1, calculated from data in [15]). The specific absorption rate (SAR, in W/kg of RF energy) at depth $z$ beneath the surface is

$$\text{SAR} = \frac{I_0(t) T_{tr}}{\rho L} e^{-z/L}. \quad (7)$$

Gournay [16] considered TA pressure generation in a half-plane of material exposed to plane wave RF radiation incident normally on the surface. The surface is either free (e.g., air) or constrained (e.g., bone), depending on its acoustic impedance relative to that of the tissue. In the present notation the peak acoustic pressures are

$$p_{\text{peak}} = \frac{p_0}{2}(1 - e^{-\tau_p/\tau_s}) \quad (\text{free surface}) \quad (8a)$$

$$= p_0(1 - e^{-\tau_p/2\tau_s}) \quad (\text{constrained surface}) \quad (8b)$$

where $p_0 = \frac{I_0 T_{tr} \Gamma}{v_s}$.

**TABLE 1. Frequency-dependent parameters for dry skin.**

| Frequency (GHz) | L (mm) | $T_{tr}$ | $\tau_{th}$ (sec) | $\tau_s$ (microsec) |
|---|---|---|---|---|
| 6 | 4.09 | 0.48 | 153 | 2.6 |
| 10 | 1.90 | 0.49 | 33 | 1.2 |
| 30 | 0.43 | 0.54 | 1.67 | 0.3 |
| 100 | 0.18 | 0.69 | 0.30 | 0.1 |
| 300 | 0.14 | 0.84 | 0.17 | 0.09 |

The thermal and stress confinement times, $\tau_{th}$ and $\tau_s$ respectively, were calculated assuming the characteristic distance scale of heating is L, the 1/e power penetration distance of a plane wave normally incident on a plane tissue surface with dielectric properties equal to those of dry skin, and $T_{tr}$ is the energy transmission coefficient from air into the tissue. Data calculated from Gabriel et al. [15].

The acoustic pulses have a duration of $\sim\tau_s$; their frequency spectrum is broad and centered at $1/2\pi\tau_s$ Hz (Figure 2). Expanding (8a) to first order in $\tau_p/\tau_s$ and expressing in terms of the pulse fluence $\varphi(I_o\tau_p$ in J/m$^2)$ yields

$$p_{\text{peak}} = \frac{\Gamma \varphi T_{tr}}{2 v_s \tau_s} \quad \tau_p \ll \tau_s \quad \begin{pmatrix} \text{free surface,} \\ \text{stress confinement} \end{pmatrix} \quad (9a)$$

$$p_{\text{peak}} = \frac{\Gamma \varphi T_{tr}}{2 v_s \tau_p} \quad \tau_p \gg \tau_s \quad \begin{pmatrix} \text{free surface,} \\ \text{stress nonconfinement} \end{pmatrix}. \quad (9b)$$

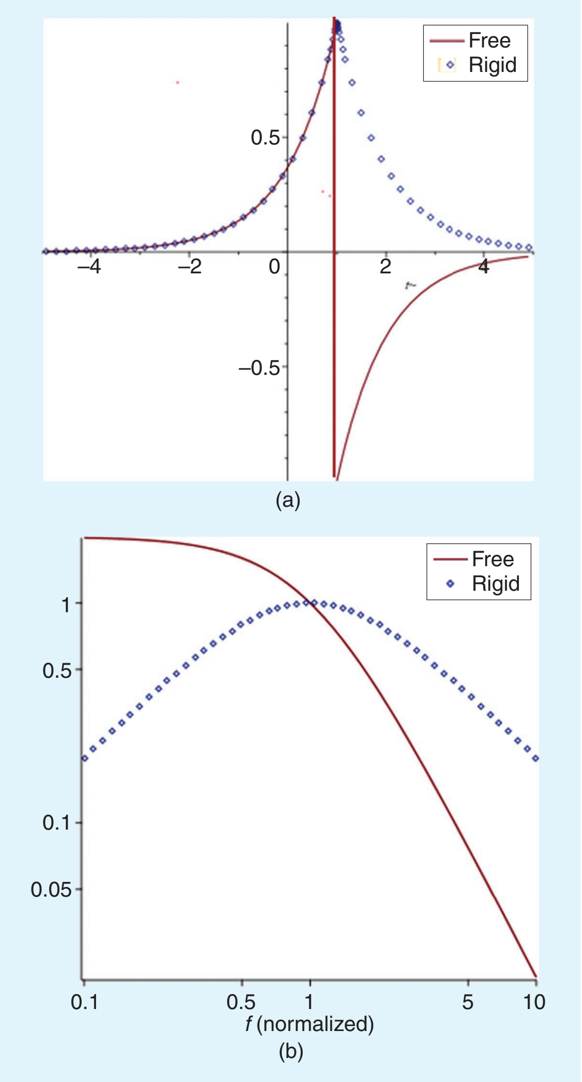


**Figure 2.** *(a) Pressure wave produced by a short pulse of microwaves incident on a plane tissue surface (time normalized to the pulsewidth), with free and rigid acoustic boundaries. The change in polarity of the wave in the medium with a free boundary is due to reflection of part of the wave from the boundary. Calculated from results in Gournay [16]. (b) Magnitude spectrum of pressure waves shown in (a), normalized to a center frequency of $1/2\pi\tau_s$ (Hz) produced by microwave pulse normally incident on a plane tissue surface with free and rigid acoustic boundary conditions.*

### Thresholds for Perception of the Acoustic Transients in the Head

Figure 3 summarizes thresholds for human perception of auditory sensations reported by Frey [4], [17], Guy et al. [8] and Cain and Rissmann [18]. To simplify the presentation, the figure only shows thresholds for pulses of varying width at single frequencies; a scattering of data from humans and experimental animals at a variety of frequencies and pulse widths are also available. Human thresholds for perception vary considerably; some subjects in these studies could not perceive them at all. Perhaps this may result from different experimental conditions or simply from individual variability in hearing thresholds. For the following discussion, a threshold of 0.4 J/m$^2$ at 2.45 GHz [8] will be used for peak pressure estimates.

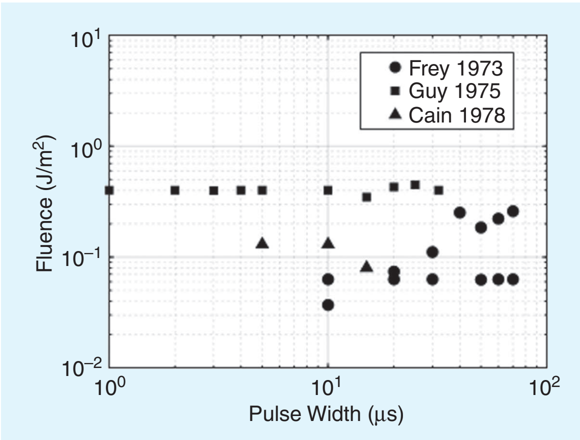


**Figure 3.** *Threshold for perception of pulses of microwave energy in human subjects in terms of fluence of incident energy density. Studies are Frey and Messenger [17] (four subjects exposed to the back of the head at 1.245 GHz); Cain and Rissmann [18] (eight subjects exposed to the top of the head at 3 GHz,); Guy et al. [8] (two subjects exposed to the back of the head at 2.45 GHz).*

### Peak Pressure Increases in the Head

Table 2(a) shows the peak SAR in the head and brain at several frequencies from a vertically polarized plane wave of 1 W/m$^2$ of frequency between 0.8 and 2.45 GHz, incident on the side or front of the head. These results were calculated by one of the present authors (Diao) using a high-resolution model of the head based on medical images [19] using numerical techniques described in [20]. Table 2(b) shows the peak pressure increase ($p_0$) produced by a plane wave of the same amplitude at higher frequencies that is incident on a homogeneous plane of tissue, from (9a). For equal-fluence pulses under stress confinement conditions, the amplitude of TA pressure waves increases rapidly with frequency, as does their frequency range [Table 2(b)].

Figures 4, 5, and 7 show the SAR patterns in the head for frontal and lateral exposure to plane waves at 2.45 GHz, while Figure 6 shows elevation plots along contours shown by the white lines that extend horizontally for a distance of 5 cm through the head. The

**TABLE 2 (a) Peak SAR in the head exposed to plane waves from 0.8–2.45 GHz. (b) Peak pressure transients induced by plane waves incident on tissue, 10–100 GHz.**

| Frequency (GHz) | Peak SAR in head (W/kg) Incident power density 1 W/m$^2$ | | Peak SAR in brain (W/kg) Incident power density 1 W/m$^2$ | |
|---|---|---|---|---|
| | Lateral | | Frontal | |
| | Head | Brain | Head | Brain |
| 0.8 | 0.31 | 0.05 | 0.42 | 0.04 |
| 1 | 0.32 | 0.04 | 0.37 | 0.04 |
| 1.5 | 0.46 | 0.05 | 0.47 | 0.05 |
| 2 | 0.56 | 0.05 | 0.40 | 0.05 |
| 2.45 | 0.46 | 0.04 | 0.35 | 0.05 |

| Frequency (GHz) | L (mm) (1/e power penetration depth) | Stress confinement time $\tau_s$, μs | $p_{peak}$ for a brief pulse of fluence 1 J/m$^2$ incident on a plane tissue surface (9a), Pa | Center frequency of acoustic pulse (MHz) | Model |
|---|---|---|---|---|---|
| 10 | 1.9 | 1.3 | 26 | 0.12 | Plane of tissue with microwave beam normally incident on an unconstrained surface (9a), tissue parameters in Table 1 |
| 30 | 0.4 | 0.3 | 127 | 0.53 | |
| 100 | 0.18 | 0.1 | 385 | 1.6 | |

peak SAR values in the head occur in the earlobe and tip of the nose, depending on the direction of the incident wave. In general, the highest SAR occurs in the skin and subcutaneous tissue outside the skull and is quite nonuniform. The SAR distribution within the brain itself is also nonuniform but is generally highest in outer regions of the brain near the dura. Thus, most of the energy absorbed from the incident beam occurs within the first 2–3 cm of the surface of the head, which reflects the short power penetration depth (1–2 cm) of 2.45-GHz microwaves in tissue. Consequently, most of the TA pressure waves are generated close to the skull as well.

From Table 2(a) one can estimate the induced peak acoustic pressures in the brain from experimentally measured thresholds for the microwave auditory effect. A rectangular pulse with fluence $\varphi$ and duration $\tau_p$ incident on the head has a power density of $\varphi/\tau_p$ W/m$^2$, and the resulting peak SAR can be obtained by scaling the SAR values for the brain listed in Table 2(a). Assuming stress confinement, a 2.45 GHz pulse with fluence of 0.4 J/m$^2$ will produce a peak acoustic pressure of 3.9 Pa within the brain.

## Is the Microwave Auditory Effect a Potential Hazard at High Exposure Levels?

Since the 1970-era studies on the auditory effect, high powered (gigawatt) pulsed microwave transmitters have been developed, largely in DEW programs in the United States and other countries. Little information is publicly available about the maximum power output of those systems, and few if any safety studies on such systems have been made public. Two recent studies examined biological effects and thermoacoustically induced pressures from what their authors considered to be maximum feasible exposure levels.

De Seze et al. [21] exposed rats to intense RF pulses that were repeated at a rate of 100 s$^{-1}$. One set of exposures (identified as "SRX") consisted of 1-ns pulses at 10 GHz at a peak power density of 20 GW/m$^2$ (fluence 20 J/m$^2$) for a total of 12,000 pulses. The second (identified as "SRS") consisted of 2.5-ns pulses at 3.7-GHz (2 GW/m$^2$ peak power density, fluence of 5 J/m$^2$) for a total of 96,000 pulses. From the modeling study by Wang et al et al. [22], we estimate that the peak acoustic pressure induced by each pulse in the brain was 50 or 200 Pa (SRS and SRX pulses, respectively). These exposures were close to the maximum that could be produced by the technology available to the investigators.

The investigators conducted a variety of behavioral tests on the rats. During the exposures, the rats were given a choice of remaining exposed or moving to a shielded compartment. They showed a strong preference for the shielded compartment; the exposure was clearly aversive to the animals. Most behavioral tests conducted after the exposures were negative; however, in one test, involving balancing on a rotating beam, the exposed rats actually performed better than unexposed controls. This suggests the absence of major vestibular effects in the rats.

After being exposed to 96,000 SRS pulses, brain tissues excised from the rats showed modest increases in levels of glial fibrillary acidic protein (GFAP), a marker of brain inflammation or damage. When followed for their remaining lifetimes, exposed rats had a sixfold increase in death rates from cancer compared to unexposed controls. The tumors chiefly occurred in soft tissues (sarcomas and fibrosarcomas) throughout the body. The cause of these effects is presently unknown; it may be a direct effect of the very high RF field levels (>0.5 MV/m in the animals' bodies), an indirect effect due to stress, or maybe something else entirely.

The study had a potentially important confounder: the animals received significant X-ray exposure (0.8 Gy) due to their proximity to the high-voltage power

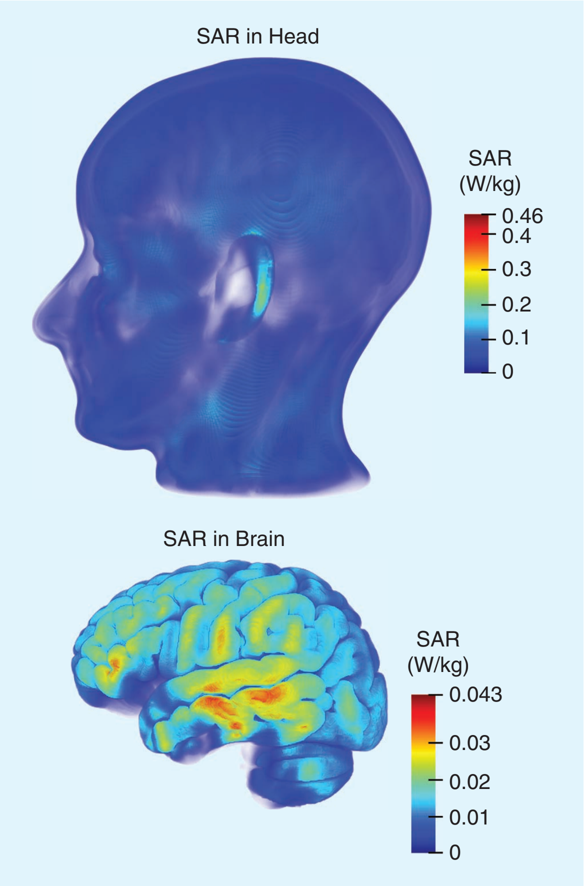


**Figure 4.** *SAR distribution in the Alvar head model with a resolution of 0.51-mm exposed to plane wave radiation from the side (2.45 GHz, at 1 W/m$^2$). The peak SAR in the head and brain are approximately 0.46 and 0.043 W/kg, respectively.*

sources in the microwave generating equipment. De Seze et al. argued that the increase in cancer was too large to be due to the X-ray exposure and attributed the effects to the microwave exposure even though they did not propose a specific mechanism for damage.

In a recent computational study, Dagro et al. [23] calculated the acoustic pressures induced in models of the human head produced by 1-GHz microwave pulses of 5 or 500 µs, each with a fluence of 50 J/m$^2$ (incident power densities of 10$^5$ or 10$^7$ W/m$^2$, respectively). These incident power densities are "within the capabilities of some commercial and military systems" the authors noted. We estimate the peak induced acoustic pressure in the brain from the shorter pulse to be ~550 Pa; Dagro et al. calculated peak pressures as high as 1.3 kPa in some regions of the brain. A person would undoubtedly find the resulting auditory stimuli to be extremely unpleasant or painful. Even at these extreme exposures, the maximum temperature increase from a single pulse was less than 0.001 K, and the exposures would have been well within currently accepted safety limits which are based on 6- or 30-min averages of exposure.

## *Hazard Mechanisms*

### Cavitation

Cavitation is the major damage mechanism from acoustic energy to brain tissue and is the limiting hazard used to formulate safety limits for ultrasound for medical examination of the brain. The relevant dosimetric quantity is the mechanical index (MI), defined as the peak rarefactional acoustic pressure in megapascals divided by the square root of the wave frequency in megahertz. The threshold for cavitation in presence of microscopic air bubbles (which facilitates cavitation) corresponds to a MI of 0.7 [24]. At a frequency of 100 kHz, this corresponds to a peak negative pressure of 100 kPa, two orders of magnitude above those estimated by Dagro et al. Transcranial ultrasound is widely used to treat a variety of neurological conditions, in which ultrasound at a few hundred kilohertz is applied to the head with peak acoustic powers that can exceed 1 MPa in the brain without apparent injury [25]. For another comparison, the calculated (acoustic) pressures are well below intracranial pressure variations due to the Valsalva maneuver (~3–4 kPa) [26]. Consequently, acoustic pressures induced in the head by pulsed microwaves at the extreme levels considered by de Seze et al. and Dagro et al. are likely to be below thresholds for acute injury of the sort that limits exposure of the brain to pulsed acoustic energy.

### Vestibular Effects

High-intensity sound waves outside the audible frequency range are known to interact with the vestibular system, causing a range of effects such as dizziness or impaired balance [27]. For example, when divers are exposed to pulsed acoustic energy while underwater, they experience vestibular effects when acoustic pressures exceed 1 kPa. In the absence of better information, this may be a useful indication of thresholds for vestibular effects from microwave-induced acoustic waves in the head. Such effects may be disabling and long-lasting even in the absence of detectable brain damage through a common but poorly understood phenomenon known as a functional neurological disorder [28].

We can expect that TA waves induced by high-energy microwave pulses might produce vestibular effects in humans. However, thresholds for any such effects are presently unknown.

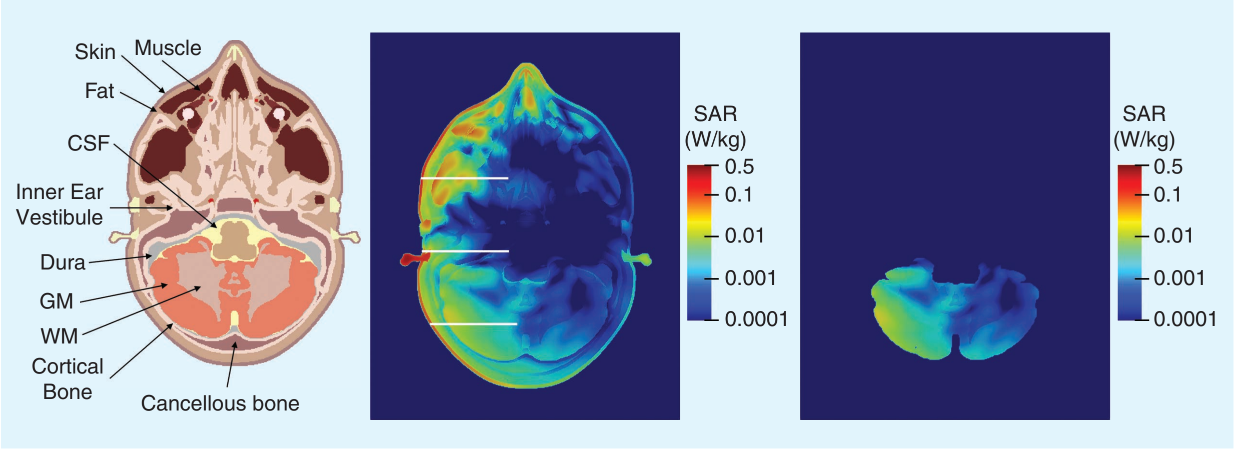


**Figure 5.** *Axial view of the SAR distribution (lateral exposure) in a horizontal plane passing through the ear canals for the Alvar head model (resolution 0.51 mm). The location of major structural features are shown. GM: gray matter, WM: white matter, CSF: cerebrospinal fluid. The vestibular system is located in the temporal bone, approximately 30 mm from the skin surface near the earlobe. The horizontal white lines indicate the contours for the SAR elevation plots shown in Figure 6.*

Thermally induced acoustic pressures in the head produced by pulsed microwaves at about 1 GHz at the high energy levels considered by de Seze et al. and Dagro et al. would elicit very strong and possibly painful auditory responses. That may not be the case with high energy pulses of millimeter-wave energy (30–300 GHz), which would produce acoustic pulses above the audible range for humans [Table 2(b)]. However, for equal pulse energy, assuming stress confinement is satisfied, millimeter waves will produce stronger acoustic pulses than 1-GHz energy [Table 2(b)]. The acoustic waves will be generated primarily in tissues outside the skull, and the acoustic pathways to the cochlea may be different than for acoustic waves from 1-GHz microwaves that are reflected within the head. The vestibular system is close to the surface of the head (Figure 5) and is highly sensitive to mechanical disturbances, which could be induced using pulsed ultrasound or infrasound as well as acoustic pulses generated thermally by pulsed microwaves.

It would be much easier to produce vestibular effects directly using acoustic energy, which could be done with readily obtained technology. If the sound waves were sufficiently far outside the frequency range of human audition (nominally, 20 Hz–20 kHz), this could be done without producing audible sensations

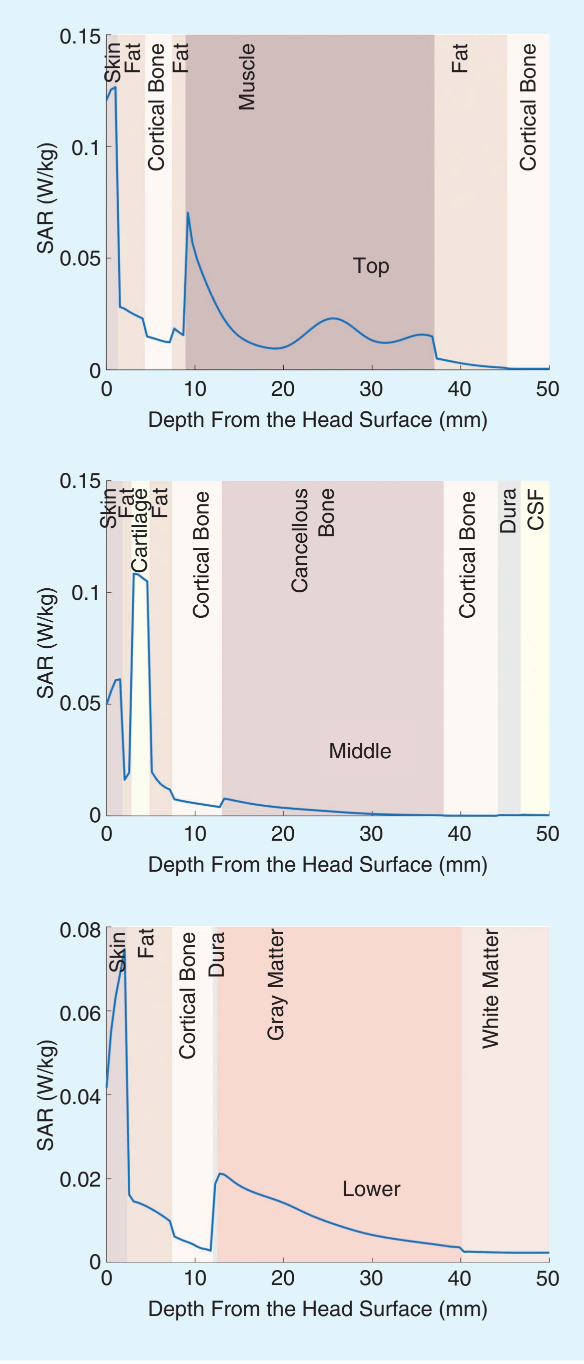


**Figure 6.** *SAR elevation plots along the top, middle, and lower lines along the axial plane shown in Figure 5 with anatomical features shown. (Exposure 2.45 GHz, 1 W/m$^2$)*

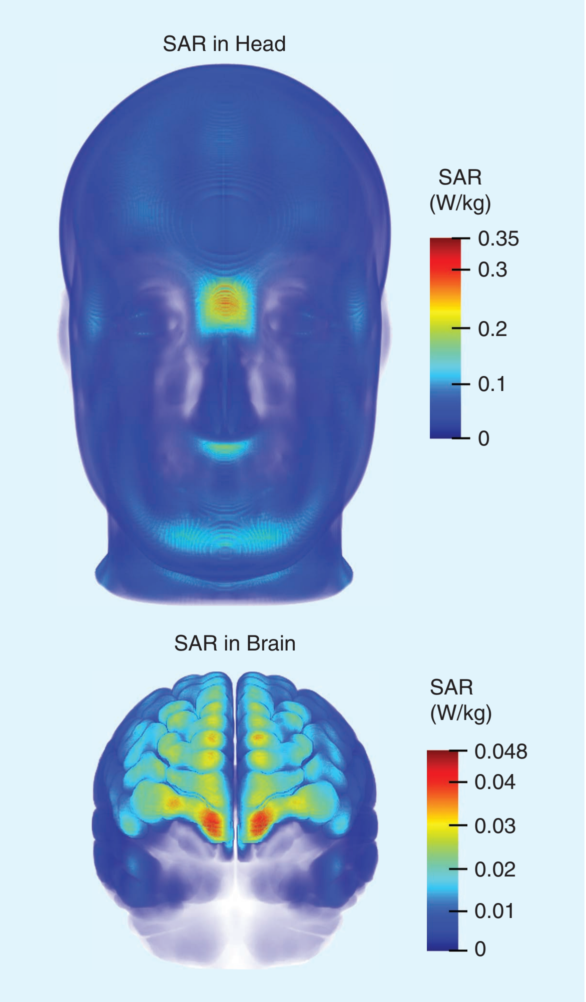


**Figure 7.** *SAR distribution (frontal exposure) in the Alvar head model with a resolution of 0.51 mm, exposed to plane wave radiation (1 W/m$^2$ at 2.45 GHz). The peak SAR in the head and brain are approximately 0.35 and 0.048 W/kg, respectively.*

in the subject. Producing similar effects using thermally induced sound from pulsed microwaves would require extreme microwave pulses to create effective sound pressures given the inefficiency of microwave to sound transduction.

No data exist that would link the microwave auditory effect to brain damage or to vestibular effects, and the thresholds for adverse effects from such exposures are not known. However, classified DEW programs in several countries are developing microwave sources that operate at high (GW) power levels. Apart from speculations about the cause of AHIs, the safety of human exposure to such energy needs to be studied.

## Were the AHIs (as well as Havana Syndrome) Caused by Pulsed Microwave Energy?

"Havana Syndrome" refers to a set of unexplained symptoms (e.g., headache, dizziness, hearing issues) first reported by U.S. diplomats in Havana and is not a recognized disease by health agencies such as the U.S. Centers for Disease Control (CDC) or the World Health Organization. Anomalous Health Incidents (AHIs) is a U.S. Government term for episodes of unexplained symptom and is likewise not a medical diagnosis [29] .

Reports of AHIs (also known as Havana Syndrome) have varied widely since the issue first became widely publicized in 2016. (See "Evolution of Havana Syndrome").

The following comments address suggestions by Lin [30], Giordano [31] as well as an expert committee of the National Academy of Science, Engineering and Medicine (NASEM) [1] that "anomalous health incidents" reported by U.S. officers in Havana and elsewhere around 2016 were most likely the result of attacks involving pulsed microwave energy with a mechanism related to the microwave auditory effect.

Thus, for example, in its 2020 report, the NASEM panel concluded that "many of the distinctive and acute signs, symptoms, and observations reported by the Department of State employees are consistent with the effects of directed, pulsed RF energy," and specifically mentioned the microwave auditory effect as the likely mechanism.

However, to date, no microwaves or other powerful pulses of energy have been detected (or at least reported by the government) accompanying the incidents. From the preceding discussion it seems that immense microwave pulses would be needed to produce biologically significant acoustic energy in the head, and we imagine that such pulses or the equipment needed to produce them would have been difficult to overlook.

However, there is clear evidence that at least some of these individuals experienced vestibular disturbances, in some cases with lasting effects that were career-ending. The NASEM report began: "An individual assigned to the U.S. Embassy in Cuba was awakened one night at home in Havana in 2016 by severe pain and a sensation of intense pressure in the face, a loud piercing sound in one ear with directional features, and acute disequilibrium and nausea."

The 19-person NASEM committee—which included distinguished physicians and neurologists, other health scientists, and engineers—interviewed eight individuals who had reported the incidents and consulted with several experts, including one with access to classified information about U.S. DEW systems. "From a neurologic standpoint," the committee concluded, "this combination of distinctive, acute, audio-vestibular symptoms and signs suggests localization of a disturbance to the labyrinth or the vestibulocochlear nerve or its brainstem connections."

The directionality of the experience that the subjects described to the NASEM panel, with a "loud piercing sound in one ear," is inconsistent with the microwave auditory effect, in which the cochlea of both sides of the head are stimulated and therefore there is no sound localization. Hypothetically, pulsed millimeter-wave energy of sufficient power level directed toward one side of the head might produce vestibular effects without eliciting auditory sensations and with a directionality such as described to the NASEM panelists. The same could be said about pulses of ultrasound or infrasound outside of the human auditory range, which would be more effective than microwaves at a given pulse energy at inducing mechanical disturbances in the head.

However, in at least one case, an employee (not among the core group of eight interviewed by the NASEM panel) reported loud sounds which were later identified as being due to Havana crickets. This led Baloh and Bartholomew to suggest that some employees were simply frightened by the sound of Cuban crickets and their discussions with other coworkers triggered a psychosocial process called mass psychogenic illness [32]. Loud sounds that could be recorded outside of a subject could not, of course, have been produced by the microwave auditory effect, and very loud crickets would not explain a "loud piercing sound in one ear" followed by the "sudden onset" of symptoms characteristic of vestibular disturbances that multiple subjects described to the NASEM committee. Because of the widespread concerns that reports of AHIs in Havana and elsewhere raised within the diplomatic and intelligence communities, some U.S. Government employees may have experienced symptoms for a variety of reasons which they attributed to AHIs. By now, hundreds of U.S. Government employees have come forward with reports of AHIs, which may have had a

## Evolution of Havana Syndrome

Anomalous health incidents (AHIs) aka the Havana Syndrome has turned into a significant issue with further scientific study, Congressional hearings, legislation (the Havana Act of 2021 [S1]), lawsuits, many podcasts, and widespread media coverage—as well as conspiracy theories on social media. The following comments illustrate the complexity of the issue as related to understanding the causes of the reported symptoms.

Extensive reviews by scientific groups have failed to identify the causes of the reported symptoms or identify any exposure that might have caused them. A follow-up study by the National Institutes of Health compared "86 U.S. government staff and family members with AHIs from Cuba, Austria, China, and other locations" with 30 "vocationally matched" government control participants. [29]). The study found "no significant differences between participants with AHIs and control participants" except "objective and self-reported measures of imbalance and symptoms of fatigue, posttraumatic stress, and depression." These symptoms reported by the AHI subjects are nonspecific (could have many causes) and may in part have had mundane causes unrelated to attacks by energy weapons.

In an accompanying editorial [S2] David A. Relman (Stanford University, the chair of the NASEM committee that examined the issue) noted the "the lack of a precise case definition, and a lack of complete details about the circumstances of AHIs and even about the referral process itself" as well as "highly variable delays between symptom onset and clinical assessment" as limitations in the NIH study. Relman called for "surveillance systems designed to rapidly detect early cases and clusters of concern across multiple U.S. government agencies."

Many ordinary citizens outside of U.S. Government employment, who would seem very unlikely to have been exposed to DEWs, consider themselves to suffer from Havana Syndrome. Others attribute voices they hear in their heads to "voice to skull" transmission via the microwave auditory effect (although quality speech transmission via the auditory effect has never been demonstrated and seems unlikely given the pulsatile nature of the stimulus). In their recent review in a medical journal, Connolly et al. cautioned physicians treating patients complaining of Havana Syndrome not to "miss other conditions that may present with similar symptoms and that might respond well to targeted treatment." [S3]. The many online reports of people suffering from "Havana Syndrome" may be due, in part, to social contagion (a well known psychosocial effect related to MPI) [S4].

Since 2016, U.S. intelligence agencies have undertaken numerous studies to identify the cause of the AHIs reported by government employees and search for possible involvement by foreign actors. The 2025 Office of the Director of National Intelligence report "Updated Assessment of Anomalous Health Incidents" summarizes the conclusions of different U.S. intelligence "components" (ICs) that have studied the issue [S5]. Five thought it was "very unlikely" a foreign actor "has used a novel weapon or prototype device to harm even a subset of the U.S. Government personnel or dependents who reported medical symptoms or sensory phenomena as AHIs." In contrast, "one IC component judges there is a 'roughly even chance' a foreign actor has used a novel weapon or prototype device to harm a small, undetermined subset of the U.S. Government personnel or dependents who reported medical symptoms or sensory phenomena as AHIs" but had "low confidence" in this conclusion. Presumably, this "small subset" would include the eight subjects interviewed by the NASEM committee that led to its conclusions about the likelihood of an energy attack.

However, neither that explanation, nor a psychogenic explanation, can be proven or disproven based on present evidence. Unless further information develops or an actual weapon is identified, this issue will not be readily resolved.

### References


[S1] Implementation of HAVANA Act of 2021, Final Rule, 89 Fed. Reg. 75639 (to be codified at 32 C.F.R. pt. 117, Oct. 3, 2024).

[S2] D. A. Relman, "Neurological illness and national security: Lessons to be learned," *JAMA*, vol. 331, no. 13, pp. 1093–1095, 2024, doi: 10.1001/jama.2023.26818.

[S3] M. Connolly, M. J. Hawkshaw, and R. T. Sataloff, "Havana syndrome: Overview for otolaryngologists," *Amer. J. Otolaryngology*, vol. 45, no. 4, 2024, Art. no. 104332, doi: 10.1016/j.amjoto.2024.104332.

[S4] A. Gaba and S. Munjal, "Havana syndrome: Social contagion or mass psychogenic illness?" *Primary Care Companion CNS Disorders*, vol. 26, no. 2, 2024, Art. no. 23cr03640, doi: 10.4088/PCC.23cr03640.

[S5] "Updated assessment of anomalous health incidents as of December 2024," Nat. Intell. Council, McLean, VA, USA, Jan. 2025. [Online]. Available: https://www.dni.gov/files/ODNI/documents/assessments/NIC-Unclassified-ICA-Updated-Assessment-AHI-March2023.pdf

variety of environmental or medical causes unrelated to conjectured attacks by energy weapons.

In summary, the evidence presented to the NASEM panel points to an energy attack of some sort to at least a few U.S. Government employees. To induce vestibular effects by the microwave auditory effect, we estimate, would require immense pulse energies, and evidence for such exposures is absent. On the other hand, there seems to have been no monitoring of the environments in which such individuals were located that would have disclosed energy attacks as they occurred. Other narratives point to psychogenic causes of the reported symptoms in some employees reporting AHIs. The microwave auditory effect remains, at present, only an intriguing hypothesis that we judge to be at the outer edges of credibility.

## Conclusion

The technology for producing high-powered microwave pulses is rapidly advancing, and it seems inevitable that some individuals will be exposed to very intense microwave pulses, if only inadvertently in workplace accidents, and the safety of such exposures needs to be examined. It would be out of the question to deliberately expose humans to such pulses. Appropriate animal studies might identify and clarify the mechanisms for brain/tissue damage from high-energy microwave pulses. Computational studies, such as those of Dagro et al. [23], could assess the acoustic pressures developed in the head by microwave exposure over a range of frequencies and direction against the head. Microwave hearing studies using much less intense pulses, such as those by Guy et al. in the 1970s, could fill out details that are presently lacking about the auditory effect and employ more subjects than the small 1970s era microwave hearing studies. Finally, the government needs to share the results of its safety investigations with experts outside of government for independent evaluation.

## References


[1] J. A. Pavlin and D. A. Relman, "An assessment of illness in US government employees and their families at overseas embassies," Nat. Academies Press, Washington DC, USA, 2020.

[2] C. K. Chou, A. W. Guy, and R. Galambos, "Auditory perception of radio-frequency electromagnetic fields," *J. Acoust. Soc. Am*, vol. 71, no. 6, pp. 1321–1334, 1982, doi: 10.1121/1.387852.

[3] A. H. Frey, "Auditory system response to radio frequency energy," *Aerosp. Med.*, vol. 32, no. 1, pp. 140–142, 1961.

[4] A. H. Frey, "Human auditory system response to modulated electromagnetic energy," *J. Appl. Physiol.*, vol. 17, no. 4, pp. 689–692, 1962, doi: 10.1152/jappl.1962.17.4.689.

[5] K. R. Foster and E. D. Finch, "Microwave hearing: Evidence for thermoacoustic auditory stimulation by pulsed microwaves," *Science*, vol. 185, no. 4147, pp. 256–258, 1974, doi: 10.1126/science.185.4147.256.

[6] C. Chou, R. Galambos, A. W. Guy, and R. H. Lovely, "Cochlear microphonics generated by microwave pulses," *J. Microwave Power*, vol. 10, no. 4, pp. 361–367, 1975, doi: 10.1080/00222739.1975.11688973.

[7] C. K. Chou, A. W. Guy, and R. Galambos, "Characteristics of microwave-induced cochlear microphonics," *Radio Sci.*, vol. 12, no. 6S, pp. 221–227, 1977, doi: 10.1029/RS012i06Sp00221.

[8] A. W. Guy, C. K. Chou, J. C. Lin, and D. Christensen, "Microwave-induced acoustic effects in mammalian auditory systems and physical materials," *Ann. N.Y. Acad. Sci.*, vol. 247, no. 1, pp. 194–218, 1975, doi: 10.1111/j.1749-6632.1975.tb35996.x.

[9] J. C. Lin, *Microwave Auditory Effects and Applications.* Springfield, IL, USA: Charles E Thomas, 1978.

[10] J. C. Lin, *Auditory Effects of Microwave Radiation*. Cham, Switzerland: Springer-Verlag, 2021.

[11] V. E. Gusev and A. A. Karabutov, *Laser Optoacoustics*. New York, NY, USA: AIP, 1993.

[12] L. V. Wang and H. Wu, *Biomedical Optics: Principles and Imaging*. Hoboken, NJ, USA: Wiley, 2007.

[13] M. Xu and L. V. Wang, "Photoacoustic imaging in biomedicine," *Rev. Sci. Instrum.*, vol. 77, no. 4, Apr. 2006, Art. no. 041101, doi: 10.1063/1.2195024.

[14] L. Bianchi, F. Cavarzan, L. Ciampitti, M. Cremonesi, F. Grilli, and P. Saccomandi, "Thermophysical and mechanical properties of biological tissues as a function of temperature: A systematic literature review," *Int. J. Hyperthermia*, vol. 39, no. 1, pp. 297–340, 2022, doi: 10.1080/02656736.2022.2028908.

[15] S. Gabriel, R. W. Lau, and C. Gabriel, "The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues," *Phys. Med. Biol.*, vol. 41, no. 11, pp. 2271–2293, 1996, doi: 10.1088/0031-9155/41/11/003.

[16] L. S. Gournay, "Conversion of electromagnetic to acoustic energy by surface heating," *J. Acoust. Soc. Am*, vol. 40, no. 6, pp. 1322–1330, 1966, doi: 10.1121/1.1910230.

[17] A. H. Frey and R. Messenger Jr, "Human perception of illumination with pulsed ultrahigh-frequency electromagnetic energy," *Science*, vol. 181, no. 4097, pp. 356–358, 1973, doi: 10.1126/science.181.4097.356.

[18] C. A. Cain and W. J. Rissmann, "Mammalian auditory responses to 3.0 GHz microwave pulses," *IEEE Trans. Biomed. Eng.*, vol. BME-25, no. 3, pp. 288–293, May 1978, doi: 10.1109/TBME.1978.326343.

[19] O. Kangasmaa, J. Kataja, and I. Laakso, "Alvar: An anatomical whole-body model with electrically anisotropic skeletal muscles for computational dosimetry," in *Proc. XXXVth General Assembly Sci. Symp. Int. Union Radio Sci. (URSI GASS)*, Piscataway, NJ, USA: IEEE Press, 2023, pp. 1–4, doi: 10.23919/URSI-GASS57860.2023.10265398.

[20] Y. Diao, E. A. Rashed, and A. Hirata, "Assessment of absorbed power density and temperature rise for nonplanar body model under electromagnetic exposure above 6 GHz," *Phys. Med. Biol.*, vol. 65, no. 22, 2020, Art. no. 224001, doi: 10.1088/1361-6560/abbdb7.

[21] R. de Seze et al., "Repeated exposure to nanosecond high power pulsed microwaves increases cancer incidence in rat," *PLoS One*, vol. 15, no. 4, 2020, Art. no. e0226858, doi: 10.1371/journal.pone.0226858.

[22] H.-Y. Wang et al., "The specific absorption rate in different brain regions of rats exposed to electromagnetic plane waves," *Sci. Rep.*, vol. 9, no. 1, 2019, Art. no. 13277, doi: 10.1038/s41598-019-49719-4.

[23] A. M. Dagro, J. W. Wilkerson, T. P. Thomas, B. T. Kalinosky, and J. A. Payne, "Computational modeling investigation of pulsed high peak power microwaves and the potential for traumatic brain injury," *Sci. Adv.*, vol. 7, no. 44, 2021, Art. no. eabd8405, doi: 10.1126/sciadv.abd8405.

[24] Safety Group of the British Medical Ultrasound Society, "Guidelines for the safe use of diagnostic ultrasound equipment," *Ultrasound*, vol. 18, no. 2, pp. 52–59, 2010.

[25] J. Wang, H. Wang, T. Jiang, Y. Wang, N. Li, and S. Qie, "Transcranial ultrasound stimulation parameters for neurological diseases: a systematic review," *Front. Neurol.*, vol. 16, 2025, Art. no. 1567482, doi: 10.3389/fneur.2025.1567482.

[26] A. Yiangou et al., "The impact of Valsalva manoeuvres and exercise on intracranial pressure and cerebrovascular dynamics in idiopathic intracranial hypertension," *Neuroophthalmology*, vol. 48, no. 2, pp. 122–133, 2024, doi: 10.1080/01658107.2023.2281433.

[27] R. J. Lubner et al., “Review of audiovestibular symptoms following exposure to acoustic and electromagnetic energy outside conventional human hearing,” *Front. Neurol.*, vol. 11, Apr. 2020, Art no. 234, doi: 10.3389/fneur.2020.00234.

[28] J. Stone and K. R. Foster, “We don’t need to choose between brain injury and ‘mass hysteria’ to explain Havana syndrome,” *Sci. Am.*, May 22, 2024. [Online]. Available: https://www.scientificamerican.com/article/havana-syndrome-we-dont-need-to-choose-between-brain-injury-and-mass

[29] L. Chan et al., “Clinical, biomarker, and research tests among US Government personnel and their family members involved in anomalous health incidents,” *JAMA*, vol. 331, no. 13, pp. 1109–1121, 2024, doi: 10.1001/jama.2024.2413.

[30] J. C. Lin, “Sonic health attacks by pulsed microwaves in Havana revisited [Health Matters],” *IEEE Microw. Mag.*, vol. 22, no. 3, pp. 71–73, Mar. 2021, doi: 10.1109/MMM.2020.3044125.

[31] J. Giordano, “Directed energy remains key suspect behind Havana syndrome,” *Nat. Defense Mag.*, Apr. 4, 2024. Accessed: Jun. 1, 2025. [Online]. Available: https://digitalcommons.ndu.edu/cdtfw-articles/3

[32] R. W. Baloh and R. E. Bartholomew, *Havana Syndrome (Switzerland Copernicus Books)*. Cham, Switzerland: Springer-Verlag, 2020.