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Some peculiarities of auditory sensations evoked by pulsed microwave fields

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Rectangularly pulsed, 800-MHz microwaves were coupled via waveguide from a 500-W source to the parietal area of the head of normal human observers (*O*s). Pulse widths from 5 to 150 μs and pulse-repetition rates (PRRs) from 50 to 20,000 pulses per second (pps) were employed. Sine-wave audio-frequency (AF) signals could be presented alternately to or concurrently with microwave pulses (RF signal) under conditions in which *O* could adjust the amplitude, frequency and phase of the AF signal. By matching timbre and loudness of the perceived RF and AF signals during a succession of psychophysical measures -- some while *O*'s head was being immersed in water -- the *O*s yielded the following results: (1) Both loudness and perceptual thresholds of the RF signal were biphasic functions of pulse width and of PRR; (2) When pulse widths increased toward 100 μs, some subjects perceived a different sound that was lower in pitch and was referred externally to the head; (3) By appropriate phasing of AF and RF signals after matching for pitch and timbre, loudness of the RF signal could be reduced below the threshold of perception; and (4) Extent of immersion of the head in water was correlated with reduced loudness of the RF signal. Some of the data are interpreted as posing explanatory difficulties for an exclusively thermoelastic mechanism of RF hearing.

1. INTRODUCTION

The RF-hearing or Frey effect, an auditory response to pulsed electromagnetic fields, has been studied for nearly two decades [cf. *Frey,* 1961 with *Frey and Messenger,* 1973]. A promising hypothesis of the mechanism of perceiving the pulses is based on thermoelastic expansion: the absorbed pulse of energy is believed by proponents of this hypothesis to produce a very small but very rapid increment of temperature in the head, which causes a slight expansion of as yet unspecified tissues, that in turn creates a wave of pressure to which the cochlea is sensitive [cf. *Foster and Finch,* 1974; *Lin,* 1976; *Guy et al.*, 1975; *Chou and Guy,* 1979].

Development of artifact-free techniques of measuring bioelectric activity [cf. *Frey et al.*, 1968; *Guy et al.*, 1975; *Tyazhelov et al.*, 1977] has recently made it possible for one to study electrophysiologically the potentials of single neurons or of neuronal populations of the auditory cortical analyzers as evoked by pulsed RF fields [*Lebovitz and Seaman,* 1977; *Chou et al.*, 1977]. However, in spite of the lengthy period of time that the RF-hearing effect has been known, relatively few studies have been made of its psychophysical properties [*Frey,* 1961, 1962, 1963; *Constant,* 1967; *Frey and Messenger,* 1973; *Guy et al.*, 1975]. Further psychophysical investigation of the phenomenon should be undertaken to evaluate the adequacy of the thermoelastic hypothesis, and to shed more light on the perceptual qualities of "radio sound." These were our aims in the studies reported here.

2. METHODS AND MATERIALS

2.1. *Sources of RF and AF signals and controls.*

The source of pulsed fields was a 0.8-GHz generator with a maximal output power of 500 watts. The source was coupled to a rectangular section of waveguide (15 × 27 cm) by a 3-meter length of coaxial cable. The open end of the waveguide was mounted firmly on a foamed plastic rest that permitted coupling of energy to the parietal area of an observer's head. Rectangular pulses of 150- to 5-μs duration could be generated at a range of pulse-repetition rates (PRRs) that extended from 50 to as high as 20,000 pulses per second (pps) for shorter pulse widths.

The rise time of discrete pulses was less than 1 μs. The pulses were either generated continuously or in trains of 0.1- to 0.5-s duration that could be presented at a rate of 0.2 to 2.0 trains s^{-1}.

A controlling device enabled the pulsed RF waves to be presented to *O* either independently of, or simultaneously with, acoustic sine waves that could be generated at the same temporal parameters. The acoustic signals were generated by a loudspeaker from which a pair of small hollow tubes extended that could be coupled directly to *O*'s ears.

A push-button switch was located on a remote control panel in ready access to *O*, who, by pressing the button, could inform an investigator of a perceptual threshold, of the appearance of a beat note, or of a shift in loudness or pitch when an RF or an acoustic stimulus, or both stimuli, were presented. The remote panel also contained controls by which *O* could regulate the amplitude of acoustic stimuli, and the time interval (phase) between acoustic and RF pulses. The control knobs on the panel were reset randomly at different positions before each *O* was tested, to control for possible artifact borne of positional cueing.

A large steel drum that contained sterile seawater permitted individual *Os* to be tested while fully submerged or with the head at various levels above the water line.

2.2. *Observers.*

Both male and female observers, all normal adults, were observed for perceptual responsiveness to RF pulses and to acoustic stimuli. Before formal observations began, each *O* was tested for his or her high-frequency auditory limit (HFAL) of perception of sinusoidal sound waves when the initial test frequency of 1 kHz was ~ 40 dB above the threshold at that frequency. Audio signals at test frequencies above 1 kHz were initially presented at the same physical intensity and then were decreased until the signal was imperceptible.

2.3. *Acoustic environment.*

The background level of noise did not exceed 40 dB and was further reduced by plugging a subject's ears with paper stoppels or by attaching the sound-conducting tubes.

3. RESULTS

3.1. *Perceptibility of audio and RF sounds.*

Three *Os* had high-frequency auditory limits (HFALs) of sound-wave detection below 10 kHz. None of these *Os* could hear 10- to 30-μs RF pulses. Of 15 *Os* with HFALs above 10 kHz, only one could not perceive the RF pulses.

3.2. *Quality of RF sounds.*

All perceptive *Os* indicated that 10- to 30-μs wide pulses delivered at repetition rates that ranged from 1000 s^{-1} to 12,000 s^{-1} (at peak field intensities at the head in excess of 0.5 W cm^{-2}) resulted in a sound with a polytonal character. The sound seemed to have its origin in the head. As the pulse-repetition rate (PRR) of pulses of constant amplitude was increased from 1000 s^{-1} to 12,000 s^{-1}, the quality of the RF sound changed in a complex manner. Loudness fell sharply as PRRs increased from 6000 to 8000 pps, while the sound became more monotonal; however, the tonal quality in no case underwent mroe than three distinguishable tonal transitions. Subjects with HFALs below 15 kHz were unable to distinguish a 5000-pps signal from that at 10,000-pps. Subjects with more extended HFALs described the pitch (subjective frequency) at 5000 pps as higher than that at 10,000 pps.

3.3. *Difference thresholds.*

Small shifts of PRR approximating 5% were only detected in the region of 8000 pps. At lower PRRs, some subjects erred on 100% of test trials in attempts to specify the direction of change, which indicates that increasing PRRs were often perceived as decreasing in frequency. When widths of pulses of constant peak amplitude were gradually increased from 5 to 150 μs, a complex loudness function was observed. Loudness increased as widths increased from 5 to 50 μs, then diminished with further increase of widths from 70 to 100 μs, and then increased again with even longer pulse widths. Figures 1 and 2 present data on perceptual thresholds as a function of PRR and of pulse width.

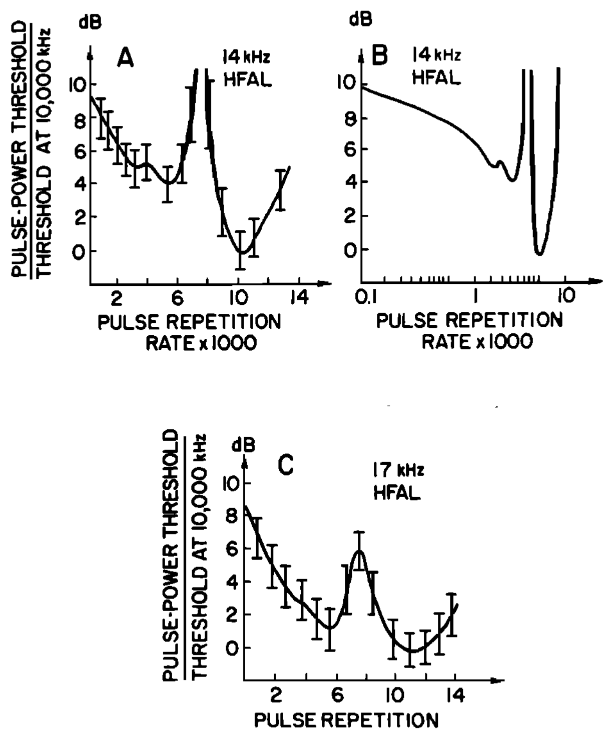

Fig. 1. Dependence of threshold of RF hearing on pulse-repetition rate (PPR). A: Curve of an observer with a high-frequency auditory limit (HFAL) of 14 kHz. B: Same as A, but logarithmically scaled. C: Curve of an observer with a HFAL of 17 kHz.

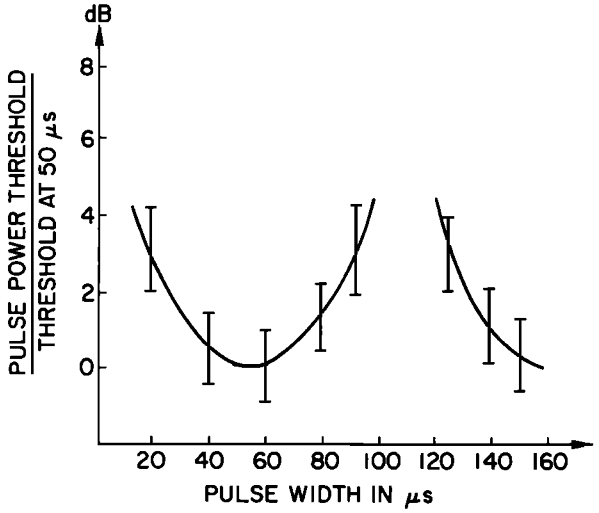

Fig. 2. Dependence of threshold of RF hearing on duration of pulse width at a PRR of 8000 pps. (Based on observers who were not perceptive of low-pitch sounds at pulse widths longer than 50 μs).

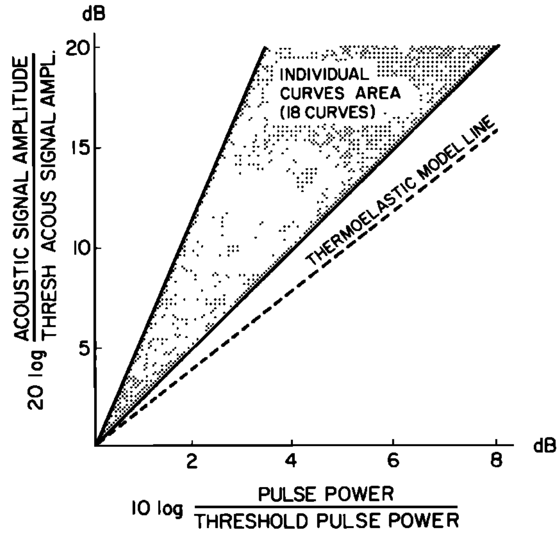

Fig. 3. Area of perceived loudness of RF pulses by 18 observers who matched AF to RF signals; audio signal = 10 kHz; RF signal = 10,000 pps. The dotted line indicates the relation predicted by the thermoacoustic model.

3.4. *Equivalence of audio and RF sounds.*

After *O*s matched the pitch and timbre of a sine-wave sound at 2 kHz to that of a train of RF pulses at 2000 pps, they were asked, first, to match the loudness of the auditory signal with that of the train of RF pulses as pulse width was varied between 5 and 150 μs; and second, to provide responses that were used to determine absolute thresholds of perception of RF pulses. Peak power was maintained at the same level in both series of measurements. The complex relation between pulse width and loudness referred to earlier was clearly evident (Figure 3).

Some of the *O*s described a new sensation when the pulse widths were increased toward 100 μs. The pitch shifted downward and the RF sound was referred externally to the head. Two *O*s with HFALs below 10 kHz could not perceive shorter RF pulses but were able to sense distinctly the longer pulses. For other *O*s, when pulses were successively shortened from 100 toward 50 μs, both the higher- and lower-pitched sounds were reported; at pulse widths less than 50 μs, the lower-pitched sound was never heard.

3.4. *Beat frequencies.*

When sinusoidal sound waves above 8 kHz were simultaneously presented with 10- to 30-μs microwave pulses that recurred at PRRs slightly above or below 8000 s^{-1}, a beat-frequency note was heard distinctly. Further, when exact matching of RF and AF frequencies was accomplished, and *O* was allowed to adjust phase of the AF signal until it opposed that of the train of microwave pulses, cancellation and loss of sensation occurred. Observers with HFALs below 15 kHz could obtain the same cancellation when a 5000-pps train of pulses was properly phased with a 10-kHz AF signal. Similarly, when the PRR was set at 800 pps, beat frequencies were obtained when the AF signal was slightly above or below harmonic frequencies of the fundamental microwave PRR.

3.5. *Water immersion.*

All of the qualitative sensory characteristics (pitch and timbre) evoked by microwave pulses of widths less than 50 μs persisted when *O*s' heads were lowered into water. Loudness, however, diminished roughly in proportion to the depth of immersion. Upon complete immersion, auditory sensations disappeared. For pulse durations longer than 50 μs, even partial immersion resulted in loss of sensation.

4. DISCUSSION

The auditory sensations evoked by trains of shorter (≤ 50 μs) microwave pulses are believed to be due to limited perception of pulsed waves at PRRs above 8000 pps. This explanation was offered earlier by *Frey* [1961], who suggested an even lower cut-off frequency of 5000 pps. Fourier analysis of the dependence of harmonic amplitude on pulse duration, if conjoined with the assumption that loudness of microwave pulses is roughly determined by the sum of squares of harmonic amplitudes for a train of pulses between 8000 and 12,000 pps, yields curves (for pulses of constant peak power) of the dependence of loudness (and thresholds of sensation) on pulse duration (Figure 4). The character of these curves is fully in accord with data reported by *Frey* [1962], *Frey and Messenger* [1973], and *Guy et al.* [1975].

The observation of beat frequencies during simultaneous presentation of RF and AF signals indicates that RF hearing is transduced at linear or quasi-linear levels of the nervous system, which agrees well with the thermoacoustic hypothesis. However, longer pulse widths that increased the mean power level produced increases in loudness that rose more rapidly than predicted by the thermoacoustic model. Moreover, the suppression of the acoustic response to a 5000-pps train of RF pulses by a 10-kHz AF signal, which was down by at least 20 dB, is at variance with the thermoacoustic model.

The smooth threshold curves above 8000 pps and the qualitative invariance of acoustic sensations as subjects' heads were immersed in water are at odds with the thesis that altering the acoustic resonant properties of the head (by immersion) would alter the perceptual quality of the RF signal. Further, because the human head is resonant at 0.8 GHz, which should be associated with a "hot spot" in its center, partial immersion in water should dampen its resonance, reduce its rate of absorption, and yield a loudness function different from that observed by us.

It is possible that the differing sensation induced by RF pulses of width greater than 50 μs can be explained by the thermoacoustic model, if not borne of other sources of sensory activation (e.g., by the teeth). Further study is needed to clarify the lower pitch and the external referencing of sound associated with longer pulses.

In summary, our data indicate that additional psychophysical studies of RF hearing are needed. The thermoacoustic model, while very promising and doubtless correct for higher peak densities and shorter pulses of irradiation, is inadequate to explain a number of pecularities of auditory sensation observed by us near threshold levels. Further development is in order.

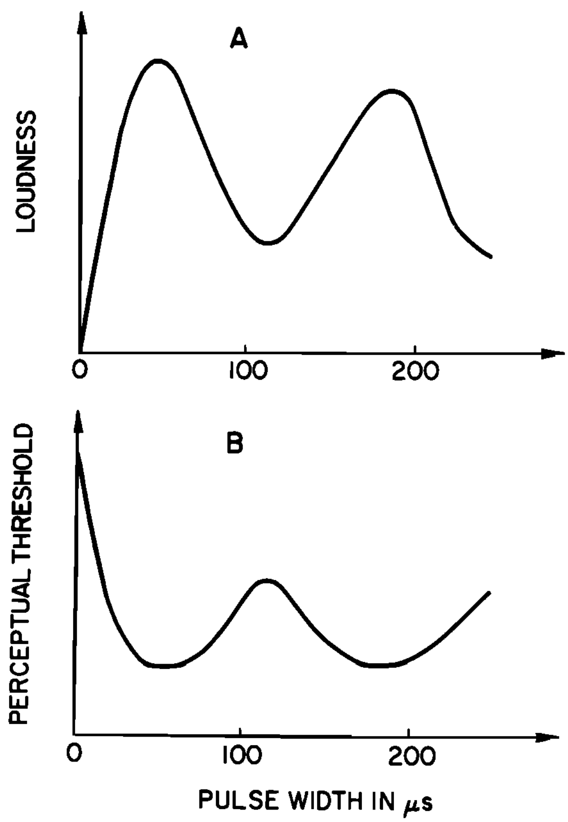

Fig. 4. A: Loudness of an RF signal as a function of pulse width. B: Threshold of detection of an RF signal as a function of pulse width. Pulses of constant amplitude recurred at 2000 pps.

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