http://www.brooks.af.mil/AFRL/HED/hedr/reports/human_exposure/humtb31.html

# TABLE 31: **RFR-AUDITORY EFFECT IN HUMANS**

| **Authors** | **Effects Sought or Examined** | **Exposure Modality** | **Effects Reported** | **Notes & Comments** |
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| Frey (1961) | RFR-auditory effect in human volunteers. | 6-μs pulses of 1.3-GHz RFR at 244 pps; 1-μs pulses of 3.0-GHz RFR at 400 pps. Ambient noise levels were about 70 and 80 dB, but with earplugs were lowered by about 25-30 dB. | The mean threshold of average power density for RFR perception was about 0.4 mW/cm$^2$ at 1.3 GHz for eight subjects and 2 mW/cm$^2$ at 3.0 GHz for seven subjects. The corresponding peak power densities were 270 and 5,000 mW/cm$^2$. Some subjects with various types of hearing losses had higher perception thresholds. | The author did not provide any variances or other statistical data.<br>The subjects were unable to match the RFR sounds to audio sine waves. With band-pass controlled white noise, best match was obtained by removing all frequencies below 5 kHz. |
| Frey (1962) | The auditory effect in volunteers, some who had an audiogram notch (a significant hearing loss) around 5 kHz. | Pulses of 125, 250, 500, 1,000, and 2,000 μs of 425-MHz RFR at 27 pps; 2.5-μs pulses of 8.9-GHz RFR at 400 pps. The noise levels were 70-90 dB; with Flent ear stopples, the noise levels were lowered by about 20 dB from 100 Hz to 2 kHz and about 35 dB at 10 kHz. | The average-power-density thresholds for perception of 125-, 250-, 500-, and 1,000-μs 425-MHz pulses were 1.0, 1.9, 3.2, and 7.1 mW/cm$^2$, with peak power densities of 300, 280, 240, and 260 mW/cm$^2$, all comparable to the 1.3-GHz threshold in Frey (1961). However, the 3-GHz peak-power threshold in Frey (1961) was much higher, about 5 W/cm$^2$, and the 8.9-GHz RFR was not perceived for peak-power densities as high as 25 W/cm$^2$, differences ascribed by the author to smaller penetration depths. | The author speculated about possible sites and mechanisms of detection of RFR pulses, including interaction of the RFR with neuron fields in the brain, but found the data to be inconclusive. Again, no statistics were presented.<br>Subjects who had the 5-kHz notch (and adequate hearing above and below 5 kHz) did not perceive RFR pulses as sound. |
| White (1963) | Elastic-wave theory of sound generation from thermal expansion due to transient surface heating. | Bombardment of the surfaces of metals, plastics, water, and piezoelectric crystal by RFR pulses or an electron beam. | Elastic waves were detected in each of the surfaces studied. Mixing (production of beat frequencies) was found when two pulses of different RFR frequencies were absorbed simultaneously. Use of a barium titanate crystal to detect elastic | The author did a theoretical analysis of the process, based on assuming an input heat flux that varies harmonically with time, to relate the amplitude of the |

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| | | | waves from heating with a single 2-μs pulse of electrons or RFR yielded easily detected signals at pulse power densities down to 2 W/cm², corresponded to a computed peak surface-temperature rise of 0.001 °C. | elastic waves to the characteristics of the input flux and thermal and elastic properties of the body. |
| Frey and Messenger (1973) | Further human studies on the RFR-auditory effect. | 1.245-GHz pulses at 50 pps; pulse width varied from 10 to 70 μs: Average power density held at 0.32 mW/cm² for peak power densities of 640 to 91 mW/cm²; peak power density held at 370 mW/cm² for average power densities of 0.19 to 1.3 mW/cm². | Each subject was requested to judge the loudness of pulsed-RFR signals relative to an initial reference signal. The median values of the loudness versus peak power density and versus average power density were graphed for each test, without deviations. The authors calculated that the peak-power-density threshold for perception of RFR pulses is 80 mW/cm², a value much lower than reported subsequently by Guy et al. (1975b) and by Cain and Rissman (1978). | No data for each subject were given. The accuracy of these results could not be evaluated because of the absence of data on the scatter of responses by each subject and because the subjective judgments of the relative loudness may be imprecise. |
| Foster and Finch (1974) | Further confirmation of the elastic theory of sound generation by RFR pulses. | They used 2.45-GHz RFR pulses in several combinations of pulse power density and pulse width, and a hydrophone immersed in salt water for detection. | The experimental results confirmed: the findings in water of White (1963); calculations showing that for short pulses, the peak sound pressure is proportional to the energy per pulse, but for long pulses it is proportional to the incident power density; and that the transition between the two peak-sound-pressure regimes occurs for pulse durations between 20 and 25 μs. | The authors also found that such acoustic transients were not obtained in water at 4 °C (where its thermal expansion coefficient is 0) and that acoustic signals between 0 and 4 °C were reverse in polarity from those for temperatures above 4 °C, results supporting the thermoelastic expansion hypothesis. |
| Sharp et al. (1974) | Transduction of RFR pulses into sound at | 14-μs pulses of 1.5-GHz RFR triggered | With a sound-level meter to measure the delay times for acoustic | The authors, while shifting the RFR absorber over |

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| | the surfaces of RFR-absorbers. | randomly at about 3 pps while regions of the subject's head were shielded with RFR absorber. The power per pulse was 4.5 kW and the pulse power density ranged from 750 to 1,500 mW/cm². | propagation for distances of 0.3 to 0.6 m between the absorber and microphone, the authors confirmed that the absorber transduced the RFR pulses into acoustic signals. Varying the carrier frequency from 1.2 to 1.6 GHz or using 2.45 GHz made little difference in the level or quality of the sound. The threshold pulse power for audibility was 275 W, yielding estimated pulse power densities in the range 46-92 mW/cm². | various areas of the subject's head, noticed that the apparent locus of the sound moved from the subject's head to the absorber. |
| Guy et al. (1975b) | RFR-auditory power-density thresholds and modulation characteristics. | Exposures of the back of the subject's head to 2.45-GHz pulses of duration varied from 1 to 32 µs. Exposures were to trains of 3 pps each, with 100 ms between pulses. The ambient noise level was 45 dB. | For Subject 1 with a normal audiogram hearing threshold, the threshold for RFR auditory perception was a constant peak energy density of 40 µJ/cm² per pulse irrespective of pulse duration. With ear plugs, the threshold was only 28 µJ/cm² per pulse. Similar results were obtained for Subject 2, who had a deep notch at 3.5 kHz in both ears, but the threshold was 135 µJ/cm² per pulse, or about three times higher than for Subject 1. | The two subjects studied were requested to signal when they perceived sound. They heard each pulse as a click, and heard pulse trains as chirps that corresponded to the pulse repetition rate. The subjects accurately interpreted Morse code transmitted by manual keying of the pulse generator. |
| Lin (1977c) | Analysis of equations of spherical models of human and animal heads of brain-equivalent material for acoustic resonant frequencies. | Theoretical paper on resonant frequencies generated by exposure to RFR pulses. | Analyzed were heads of guinea pigs, cats, and human adults and infants. The results showed that the fundamental and higher-harmonic frequencies produced by RFR pulses are independent of carrier frequency, but dependent on head size, with the fundamental frequency inversely proportional to the radius of the head. | The theoretically predicted fundamental frequencies for humans were 13 kHz for an adult and 18 kHz for an infant. |

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| Cain and Rissman (1978) | Experimental study of RFR-auditory effect in 2 cats, 2 chinchillas, 1 beagle, 8 humans. | 5-, 10-, 15-, or 20-µs pulses of 3.0-GHz RFR at 1 pulse every 2 seconds. The humans wore ear muffs during exposure, to reduce the ambient noise level (to 45 dB). | Subjects 1-5 could hear 15-µs pulses, with peak-power-density thresholds of 300, 300, 300, 600, and 1,000 mW/cm². They also could hear 10-µs pulses, with thresholds of 1,800, 225, 600, 2,000, and 2,000 mW/cm² . Only Subject 1 could hear 5-µs pulses, with a threshold of 2,500 mW/cm². By contrast, Subjects 6-8 could not hear 5-, 10-, or 15-µs pulses at the highest peak power density but could hear 20-µs pulses. In summary, 300 mW/cm² can be taken as the nominal human pulse-power-density threshold for pulse durations of 10 µs or longer. | Only results for the humans are summarized here. Seven subjects were given standard audiograms, and the thresholds for binaural hearing were determined for frequencies in the range 1-20 kHz.<br>The authors had exposed humans to pulses of 3.0-GHz RFR at peak power densities as high as 2,500 mW/cm² with no apparent ill effects. |
| Tyazhelov et al. (1979) | The qualities of the sounds perceived by humans from exposure to RFR pulses. Small hollow tubes from a speaker to the ears were used to present audiofrequency sounds without or concurrent with the RFR. | The parietal area of each subject's head was exposed to 800-MHz RFR pulses of widths 5 to 150 µs, presented either at a pulse repetition rate (PRR) of 50 to 2,000 pps or pulse trains lasting 0.1 to 0.5 seconds at a rate of 0.2 to 2.0 trains per second. | Three subjects who had HFALs below 10 kHz could not perceive 10-30 µs pulses, results that were consonant with those of Cain and Rissman (1978). Only 1 Of 15 subjects with HFALs above 10 kHz could not hear the pulses. Subjects with HFALs below 15 kHz were unable to distinguish between the sounds from a 5,000-pps and a 10,000-pps signal, and subjects with more extended HFALs heard a higher pitch for a 5,000-pps signal than a 10,000-pps signal. Subjects reported hearing beat-frequency notes when presented acoustic tones above 8 kHz concurrently with 10-µs to 30-µs pulses at PRRs just above or below 8 kHz; the subjects could cancel the perception of the RFR and audio when matching them in frequency, amplitude, and phase. | The high-frequency auditory limit (HFAL) of each subject was tested for tones from 1 kHz upward. The subjects had means for varying amplitude, frequency, and phase of the audio signals to try to match their timbre and loudness to the perceived RFR.<br>The authors suggested that many of their results are consistent with the thermoelastic hypothesis, but that others, such as the suppression of the perception of a 5,000-pps train of RFR pulses by a 10-kHz acoustic tone, were at variance with that model. |

## 3 STUDIES OF HUMAN VOLUNTEERS--OTHER RFR EFFECTS

### 3.1 THE RFR-AUDITORY EFFECT

Humans near some types of pulsed radar transmitters can perceive single pulses or pulse trains of RFR as audible clicks without the use of electronic receptors. As discussed below, there is considerable experimental evidence supporting the hypothesis that an RFR pulse having a peak power density and duration within specific limits can produce a transient thermal gradient in the head large enough to generate a transient elastic wave at a boundary between regions of dissimilar dielectric properties, and that this wave is transmitted by bone conduction to the middle ear, where it is then perceived by normal cochlear mechanisms as a click. Persons with impaired hearing are not able to hear such clicks, and animals with destroyed cochleas (inner ears) do not exhibit RFR-pulse-induced evoked responses in the brainstem. This phenomenon had attracted considerable interest because it was often cited as evidence that nonthermal effects can occur and because an initial hypothesis was that a possible mechanism for perception is direct stimulation of the central nervous system by RFR.

Frey (1961) exposed human volunteers to either 6-μs pulses of 1.3-GHz RFR at 244 pulses per second (pps) (0.0015 duty factor) or to 1-μs pulses of 3.0-GHz RFR at 400 pps (0.0004 duty factor). The mean threshold of average power density for RFR perception was about 0.4 mW/cm² at 1.3 GHz for eight subjects and 2 mW/cm² at 3.0 GHz for seven subjects. The corresponding peak power densities were about 270 and 5,000 mW/cm². (No variances or other statistical data were given.) The ambient noise levels were respectively about 70 and 80 dB, but earplugs decreased the noise by about 25-30 dB.

The subjects were unable to match the RFR sounds to audio sine waves. With white noise controlled by a variable band-pass-filter, best match was obtained by removing all frequencies below about 5 kHz.

Four subjects with various degrees of hearing loss (for air-conducted and bone-conducted sound) were tested for perception of the 1.3-GHz RFR. Subject 1 with significant hearing loss of both kinds above about 2 kHz was unable to perceive the RFR sound at intensities 30 times above the threshold. Subject 2, who had bilateral severe air-conduction loss (about 50 dB) but moderate bone-conduction loss (about 20 dB), was able to perceive the RFR sound at about the threshold level. Subject 3, with tinnitus and bilateral hearing loss ranging from about 10 dB at 250 Hz to 70 dB at 8 kHz for air conduction, more severe loss for bone conduction, and who had been diagnosed as having neomycin-induced nerve deafness, was unable to perceive the RFR. Subject 4, who had normal bilateral air-conduction hearing to about 4 kHz but severe bilateral bone-conduction loss also could not perceive the pulses. The author concluded that for perception of RFR as sound, a person must be able to hear sound above about 5 kHz, but not necessarily by air conduction.

In another study, however, Frey (1962) found that some subjects who had an audiogram notch (significant hearing loss) around 5 kHz (and adequate hearing above and below 5 kHz) did not perceive RFR pulses as sound. In this study, the RFRs used were 425-MHz pulses of 125, 250, 500, 1,000, and 2,000 μs at 27 pps (respective duty factors of 0.0034, 0.0068, 0.0135, 0.027, and 0.054) and 2.5-μs pulses of 8.9-GHz RFR at 400 pps (duty factor 0.001). The ambient noise levels were 70-90 dB and the subjects wore Flent antinoise ear stopples, which diminished the ambient levels by about 20 dB from 100 Hz to 2 kHz and by about 35 dB at 10 kHz.

The average-power-density thresholds for perception of 125-, 250-, 500-, and 1000-μs pulses of 425-MHz RFR were respectively 1.0, 1.9, 3.2, and 7.1 mW/cm², and the corresponding peak power densities were 300, 280, 240, and 260 mW/cm² (again without statistical data). (The threshold for 2,000-μs pulses of 425-MHz RFR was not determined because of inadequate instrumentation.) Thus, all four 425-MHz peak-power values were comparable to the 1.3-GHz threshold previously found (Frey, 1961), implying insensitivity to frequency in this range. However, the previously found 3-GHz peak-power threshold was considerably higher, about 5 W/cm², and the 8.9-GHz RFR was not perceived for peak-power densities as high as 25 W/cm². The author suggested that the rise in perception threshold from 1.3 GHz upward was related to the dependence of penetration depth on frequency. Noting the high ambient noise levels, he also suggested that the thresholds would be lower in quieter environments.

Frey (1962) also speculated about the possible sites and mechanisms of detection of RFR pulses, including RFR-induced changes of the electrical capacitance between the tympanic membrane and the oval window, detection in the cochlea, and interaction of the RFR with neuron fields in the brain. He discounted the first possibility because of the insensitivity of the RFR-hearing effect to head orientation relative to the RFR source, and indicated that the then-current experimental results were inconclusive about the other two possibilities.

Frey (1967) subsequently tried to resolve this point by studying the potentials evoked in the cat brain by exposure to 10-μs pulses within the range 1.2-1.5 GHz. However, the results were not conclusive and may have contained artifact.

Frey and Messenger (1973) exposed humans to pulsed 1.245-GHz RFR at 50 pps in an RFR anechoic chamber. In one set of experiments, the average power density was held at 0.32 mW/cm² and the pulse width was varied from 10 to 70 μs in 10-μs increments, yielding peak power densities from 640 to 91 mW/cm². In another set, the peak power density was held at 370 mW/cm² and the pulse width was varied over the same range, yielding average power densities from 0.19 to 1.3 mW/cm².

Four subjects with clinically normal hearing were given three trials each. The start of each trial was signaled optically. Following a variable interval of up to 5 seconds, each subject was first given a pulsed RFR signal for 2 seconds, the perceived loudness of which was to be taken as reference level 100. About 5 seconds later, the test RFR signal was presented for 2 seconds, and the subject was requested to indicate its numerical loudness relative to the reference. The results were displayed as logarithmic plots of the median values of perceived loudness versus peak power density and versus average power density. The point plotted for each test condition was the median value, without deviations, for all subjects and repetitions; no individual data were given.

In the peak-power-density plot, the loudness rose sharply from about 3 at 91 mW/cm² (70-μs pulses) to 60 at 125 mW/cm² (50-μs pulses); at the higher power densities, the sound level increased more slowly to a slightly rising plateau: to about 100 at 210 mW/cm² (30-μs pulses), 120 at 315 mW/cm² (20-μs pulses), and a slightly lower value at 630 mW/cm² (10-μs pulses). The plateau indicated that there is an optimal pulse-width band within which the perceived loudness depends on the peak power density. The author ascribed the loudness decrease at 630 mW/cm² to 10-μs pulses being shorter than optimal pulse width.

The plot of median loudness versus average power density showed more scatter, with the points ranging from about 60 at 0.19 mW/cm² (10-μs pulses) to a relatively flat maximum of 100 at 0.55 mW/cm² (30-μs pulses), diminishing to about 40 at 1.29 mW/cm² (70-μs pulses). The 1.29-mW/cm² dip was ascribed to 70-μs pulses being longer than optimal pulse width.

From their data, Frey and Messenger (1973) calculated that the peak-power-density threshold for perception of RFR pulses is about 80 mW/cm², a value much lower than those reported subsequently by Guy et al. (1975b) and by Cain and Rissman (1978), discussed later. In the absence of information on scatter of the responses by each subject and because subjective judgments of relative loudness may be imprecise, the accuracy of the results of Frey and Messenger (1973) could not be evaluated.

White (1963) reported that when the surface of a body is transiently heated by RFR-absorption (or electron bombardment), elastic waves are produced on the surface due to its thermal expansion. The author analyzed this process theoretically, with emphasis on the case of the input heat flux that varies harmonically with time, to relate the amplitude of the elastic waves to the characteristics of the input flux and the thermal and elastic properties of the body. Experiments with both electron impact and RFR-absorption verified the proportionality of the stress wave amplitude and absorbed power density, results that correlated well with the thermal and elastic properties of the heated medium.

The elastic waves were detected in all metals tested, in several carbon-loaded plastics, in water, and in a barium titanate piezoelectric crystal coated with silver. Mixing (the production of beat frequencies) was observed when two pulses of different RFR frequencies were absorbed simultaneously. A comparison of the elastic-wave stress amplitude with the radiation pressure showed that the former may be much greater than the latter, as demonstrated experimentally. When a barium titanate crystal was used to detect the elastic waves produced, heating by a single 2-μs pulse of electrons or RFR produced easily detectable signals at pulse power densities down to 2 W/cm², which corresponded to a computed peak surface-temperature rise of about 0.001°C and which produced piezo-electric-crystal voltages ranging from about 1 to more than 60 mV per kW/cm² of absorbed power density.

Foster and Finch (1974) confirmed the findings of White (1963) that RFR pulses can produce acoustic transients in water, and showed by calculation that for short pulses, the peak sound pressure is proportional to the energy per pulse, whereas for long pulses, it is proportional to the incident power density. Using 2.45-GHz RFR in several combinations of pulse power density and pulse duration and a hydrophone immersed in saline (0.15-N KCl), they found that the transition between the two regimes occurs for pulse durations between 20 and 25 μs. The authors noted that the dependence of sound pressure on pulse duration and incident peak power density is consistent with those of Frey and Messenger (1973) at 1.245 GHz. They also found that such acoustic signals were not obtained in water at 4°C (at which its thermal expansion coefficient is zero) and that the transient acoustic signal between 0 and 4°C was reverse in polarity from that for temperatures above 4°C, results that support the thermoelastic expansion hypothesis.

Sharp et al. (1974), in an experiment involving shielding regions of a subject's head from 1.5-GHz RFR pulses with RFR absorber, noticed that the apparent locus of the perceived sound moved from the head to the absorber. By using a sound-level meter to measure the delay times for acoustic propagation for distances of 0.3 to 0.6 m between the absorber and the microphone, they confirmed that the RFR pulses were transduced by the absorber into acoustic signals. The pulses were 14 μs long and were randomly triggered at about 3 pps. By calculation, the power per pulse was 4.5 kW and the pulse power densities were 7.5-15 kW/m² (750-1,500 mW/cm²) for the 0.3-0.6 m range of separations above.

Subsequent tests by Sharp et al. (1974) showed that varying the carrier frequency from 1.2 to 1.6 GHz or using 2.45 GHz made little difference in the level or quality of the sound. In addition, detectable sounds could be produced with various sizes and shapes of absorber, including pieces as small as 4 mm square by 2 mm thick, and in various types of absorber and in crumpled aluminum foil. The threshold pulse power for audibility was 275 W, yielding estimated pulse power densities in the range 0.46-0.92 kW/m² (46-92 mW/cm²). Tests were also done with constant pulse repetition rates up to 500 pps, with the finding that: "The sound produced from the absorber seemed to track the repetition rate of the microwave pulses."

Guy et al. (1975b) determined power-density thresholds and modulation characteristics for the RFR-auditory effect in two volunteers. The authors exposed the back of the head of the two humans to RFR at 15 to 30 cm from the aperture of a horn in an anechoic chamber at an ambient noise level of 45 dB, with RFR-absorbent material around the vicinity of the subject to eliminate reflections. The RFR consisted of 2.45-GHz pulses of duration that was varied from 1 to 32 μs. For each duration, the RFR was presented in trains of 3 pps, with 100 milliseconds between pulses. In each case, the subject signaled when an auditory sensation was perceived. From standard audiograms taken prior to exposure, the hearing threshold of Subject 1 was normal, but Subject 2 had a deep notch at 3.5 kHz in both ears for both air and bone conduction.

For Subject 1, the threshold for RFR auditory perception was found to be a constant peak energy density (the product of peak power density and pulse duration) of 40 μJ/cm² per pulse irrespective of pulse duration. At 3 pps, the corresponding average power density was 0.12 mW/cm². When Subject 1 wore ear plugs, the threshold peak was only 28 μJ/cm² per pulse. The threshold for a pair of pulses spaced within several hundred microseconds was the same as for one pulse with the same total energy as the pair. Similar results were obtained for Subject 2, but the threshold peak energy density was 135 μJ/cm² per pulse, about threefold higher than for Subject 1.

The authors remarked that each pulse was perceived individually by the subjects as a click and that trains of short pulses were heard as chirps of tones that corresponded to the pulse repetition rate. In addition, when the pulse generator was keyed manually, digital (Morse) code transmitted thereby could be interpreted accurately by the subjects.

The authors also studied the RFR-auditory effect in laboratory animals. Those studies are to be discussed in one of the planned reports on specific topics by the authors of the present report, as mentioned in the Introduction.

Guy et al. (1975b) and Lin (1976a, b; 1977a, b, c) analyzed postulated mechanisms for the conversion of RFR energy into acoustic energy in lossy dielectric materials. They concluded that thermal expansion forces induced by pulsed RFR, which are proportional to the square of the peak electric field, are much larger than the radiation pressure or the electrostriction produced by the same RFR pulses, and can generate in the head acoustic waves of the requisite magnitude for the hearing effect.

In Lin (1977c), equations developed for a spherical model of the head consisting of brain-equivalent material were used to obtain the acoustic resonant frequencies generated in the heads of guinea pigs, cats, and human adults and infants by exposure to RFR pulses. The results showed that the (fundamental and higher-harmonic) frequencies produced by RFR pulses are independent of the carrier frequency, but are dependent on head size, and specifically that the fundamental frequency is inversely proportional to the radius of the head. For humans, the predicted fundamental frequencies were 13 kHz for an adult and 18 kHz for an infant.

Cain and Rissman (1978) used 3.0-GHz RFR pulses to investigate the RFR-auditory effect in two cats, two chinchillas, one beagle, and eight human volunteers. For the animals, surface or brainstem-implanted electrodes were used to measure the responses evoked by audio clicks from a speaker and the responses to 5-, 10-, and 15-μs pulses. The results for the animals are to be discussed in the planned report mentioned above.

The eight humans were given standard audiograms for both air-conducted and bone-conducted sound. In addition, because the audiograms did not test hearing above 8 kHz, binaural hearing thresholds were determined for seven of the subjects for tone frequencies in the range 1-20 kHz. After those tests, the subjects were presented with 5-, 10-, 15-, and 20-μs RFR pulses at 1 pulse every 2 seconds. Each subject wore foam ear muffs during exposure, to reduce the ambient noise level (to 45 dB).

Subjects 1-5 could hear 15-μs pulses as clicks; their peak-power-density thresholds were respectively 300, 300, 300, 600, and 1,000 mW/cm². Subjects 1-5 could also hear 10-μs pulses, with peak-power-density thresholds of 1,800, 225, 600, 2,000, and 2,000 mW/cm². The only person able to perceive the 5-μs pulses was Subject 1, with a peak-power-density threshold of 2,500 mW/cm². By contrast, Subjects 6-8 could not hear 5-, 10-, or 15-μs pulses at the highest available peak power density but could perceive 20-μs pulses.

The authors did not find a correlation between the RFR results and the standard audiograms. However, they did note that a strong correlation existed between perception of RFR and hearing ability above 8 kHz as determined from the binaural thresholds. They also stated that their results are consistent with the hypothesis that a pressure wave in the human head induced by short RFR pulses contains a significant part of its energy above 8 kHz.

In brief summary of the study with human volunteers by Cain and Rissman (1978), only Subjects 1-3 could perceive 15-μs pulses, with a pulse-power-density threshold as low as 300 mW/cm² (energy-density threshold 4.5 μJ/cm²). Only Subject 2 could hear 10-μs pulses, with 225 mW/cm² (2.3 μJ/cm²) as the threshold; the thresholds for the other subjects were much higher than 300 mW/cm². Only Subject 1 could hear 5-μs pulses, but with a threshold of 2,500 mW/cm². Those thresholds were for 45 dB of ambient noise and could be higher in noisier environments. Thus, 300 mW/cm² can be taken as the nominal human RFR-hearing pulse-power-density threshold for pulse durations of about 10 μs or longer. It is noteworthy that these authors had exposed human volunteers to pulses of 3.0-GHz RFR at peak power densities as high as 2,500 mW/cm² with no apparent ill effects.

Tyazhelov et al. (1979) studied the qualities of the sounds perceived by humans from exposure to 800-MHz pulses. The parietal area of each subject's head was exposed to the open end of a waveguide fed from a 500-W source. The ambient noise level did not exceed 40 dB and was reduced by plugging the ears with stoppels or sound-conducting tubes. The pulse durations ranged from 5 to 150 μs. The pulses were presented either continuously at 50 to 2,000 pps (the latter for short pulse durations, to limit the average power density) or in pulse trains 0.1 to 0.5 seconds in duration at rates of 0.2 to 2.0 trains per second. Each person could be presented with sinusoidal audiofrequency (AF) sound waves independently of, or concurrently with, the pulsed RFR. The AF signals were presented to the subject by means of a pair of small hollow tubes extending from a speaker to the ears. The subjects had means for adjusting the amplitude, frequency, and phase of the AF signal to try to match timbre and loudness of the perceived RFR.

The high-frequency auditory limit (HFAL) of each subject for tones from 1 kHz upward was tested. Three subjects had HFALs below 10 kHz and could not perceive 10-30 µs RFR pulses, results that were consonant with those of Cain and Rissman (1978). Of 15 subjects with HFALs above 10 kHz, only one could not perceive the RFR pulses.

All of the perceptive subjects noted that 10-30 µs pulses delivered at 1,000 to 12,000 pps at peak power densities exceeding 500 mW/cm² produced sounds of polytonal character that seemed to originate in the head, and that the quality of the sound changed with increasing pulse repetition rate (PRR) in a complex manner. Loudness diminished sharply and the sound became more monotonal as the PRR was increased from 6,000 to 8,000 pps, but no more than three distinguishable tonal transitions occurred. Subjects with HFALs below 15 kHz were unable to distinguish between the sounds perceived from a 5,000-pps and a 10,000-pps signal, and subjects with more extended HFALs reported that the pitch for a 5,000-pps signal was higher than for a 10,000-pps signal.

The subjects were able to detect small (5%) shifts of PRR only in the 8,000-pps region. At the lower PRRs, the subjects erred on 100% of tests to detect the direction of PRR changes, indicating that increases of PRR were often perceived as decreases in pitch. For pulses of constant peak amplitude, loudness was perceived to: increase with duration from 5 to 50 µs, decrease from 70 to 100 µs, and increase again for 100 µs and upward. Such patterns of perception were exemplified by plots of threshold pulse power (normalized to the 10-kHz PRR threshold) versus PRR for a subject with a 14-kHz HFAL and for the another subject with a 17-kHz HFAL. The curves were roughly W-shaped, each with a central relative maximum at about 8 kHz. Also shown was a plot of mean threshold pulse power (normalized to the threshold at 50-µs pulse duration) for subjects unable to perceive any sounds for pulses longer than 50 µs. This curve was also W-shaped, with a central relative maximum within the range 100-120 µs of pulse duration.

After subjects matched the pitch and timbre of a 2-kHz acoustic tone to the perceived sound of a train of RFR pulses at 2,000 pps, they were asked to match the loudness of the acoustic tone with the loudness of the perceived pulses while the pulse duration was varied between 5 and 150 µs with the peak power held constant. No data were given. Instead, the relation between the ratio of the acoustic signal amplitude to the pulse power for the subjects (both quantities normalized to their respective thresholds) were merged into a shaded area bounded by two straight lines through the origin. That graph also showed a straight line through the origin stated by the authors to represent the theoretical relationship between these quantities as predicted from the thermoelastic model. The entire shaded area was above the theoretical line, i.e., the ratios of acoustic amplitude to pulse power for all of the subjects were reported to be larger than predicted.

When acoustic tones above 8 kHz were presented concurrently with 10-µs to 30-µs pulses at PRRs slightly above or below 8 kHz, the subjects reported hearing beat-frequency notes. In addition, for a PRR of 800 pps, similar beat frequencies were perceived when the acoustic frequency was set slightly above or below harmonics of the PRR. Moreover, when the tone and PRR frequencies were matched and the subjects were allowed to vary the phase of the acoustic tone, cancellation of perception of the two stimuli could be achieved. By proper phasing, subjects with HFALs below 15 kHz could also achieve perception cancellation between a 10-kHz acoustic signal and a 5-kHz train of pulses.

The authors reported that the sensory characteristics (pitch and timbre) evoked by RFR pulses less than 50 µs in duration also were perceived when the heads of the subjects were lowered into seawater, with loudness diminishing roughly in proportion to the immersion depth and vanishing entirely with total immersion. For pulses longer than 50 µs, even partial immersion resulted in loss of perception.

In their discussion, the authors suggested that many of their results are consistent with the thermoelastic hypothesis, but that others, such as the suppression of the perception of a 5,000-pps train of RFR pulses by a 10-kHz acoustic tone, were at variance with that model.

BACK TO CONTENTS

### 3.1.1 SUMMARY ON THE RFR-AUDITORY EFFECT IN HUMANS

The results of the various investigations of the RFR-auditory effect in human volunteers are summarized in Table 31.

**TABLE 31: RFR-AUDITORY EFFECT IN HUMANS**

CLICK HERE FOR A DISPLAY OF TABLE 31.

### 3.1.2 CONCLUSIONS

From a variety of studies of the RFR-auditory effect in humans, [Frey (1961, 1962), White (1963), Frey and Messenger (1973), Foster and Finch (1974), Sharp et al. (1974), Guy et al. (1975b), Lin (1977c), Cain and Rissman (1978)], considerable understanding has been achieved about the interaction mechanisms that give rise to the effect. The book by Lin (1978) presents detailed discussions of the various mechanisms that had been proposed for the effect, and the experimental evidence that supports the theory that the effect is due to induction thermoelastic waves by RFR pulses at a boundary between tissues of dissimilar dielectric properties within the head, with propagation of the waves to the auditory system. Noteworthy are the findings of several studies that persons with specific hearing impairments are unable to perceive RFR pulses; the finding of Foster and Finch (1974) that the effect does not occur in water at 4°C, where its thermal expansion coefficient is zero; and the peak-energy-density and peak-power-density thresholds for perception determined by Guy et al. (1975b) and Cain and Rissman (1978). [A peak power density of 300 mW/cm² is taken as the nominal perception threshold for humans of RFR pulses 10 μs or longer.]

However, the subsequent unusual findings of Tyazhelov et al. (1979) may indicate that specific aspects of the phenomenon are worth further study. On the other hand, it is noteworthy that Cain and Rissman (1978) had exposed human volunteers to pulses of 3.0-GHz RFR at peak power densities as high as 2,500 mW/cm² with no apparent ill effects. Thus, it is unlikely that persons perceiving RFR pulses would be affected adversely.