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Acoustic Weapons - A Prospective Assessment

Jürgen Altmann[a]

Acoustic weapons are under research and development in a few countries. Advertised as one type of non-lethal weapon, they are said to immediately incapacitate opponents while avoiding permanent physical damage. Reliable information on specifications or effects is scarce, however. The present article sets out to provide basic information in several areas: effects of large-amplitude sound on humans, potential high-power sources, and propagation of strong sound.

Concerning the first area, it turns out that infrasound - prominent in journalistic articles - does not have the alleged drastic effects on humans. At audio frequencies, annoyance, discomfort and pain are the consequence of increasing sound pressure levels. Temporary worsening of hearing may turn into permanent hearing losses depending on level, frequency, duration etc.; at very high sound levels, even one or a few short exposures can render a person partially or fully deaf. Ear protection, however, can be quite efficient in preventing these effects. Beyond hearing, some disturbance of the equilibrium, and intolerable sensations mainly in the chest can occur. Blast waves from explosions with their much higher overpressure at close range can damage other organs, at first the lungs, with up to lethal consequences.

For strong sound sources, mainly sirens and whistles can be used. Powered, e.g., by combustion engines, these can produce tens of kilowatts of acoustic power at low frequencies, and kilowatts at high frequencies. Using explosions, up to megawatt power would be possible. For directed use the size of the sources needs to be on the order of 1 meter, and the required power supplies etc. have similar sizes.

Propagating strong sound to some distance is difficult, however. At low frequencies, diffraction provides spherical spreading of energy, preventing a directed beam. At high frequencies, where a beam is possible, non-linear processes deform sound waves to a shocked, saw-tooth form, with unusually high propagation losses if the sound pressure is as high as required for marked effects on humans. Achieving sound levels which

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a Experimentelle Physik, Universität Dortmund, Germany; Bochum Verification Project, Institut für Experimentalphysik, Ruhr-Universität Bochum, Germany. This study was begun during a one-month research stay at the Peace Studies Program of Cornell University, Ithaca NY, U.S., funded by a grant from the John D. and Catherine T. MacArthur Foundation. It was finished at Dortmund University with funds from the Ministry of Science and Research of the State of Nordrhein-Westfalen, Germany.

would produce aural pain, equilibrium problems, or other profound effects seems unachievable at ranges above about 50 m for meter-size sources. Inside buildings, the situation is different, especially if resonances can be exploited.

Acoustic weapons would have much less drastic consequences than the recently banned blinding laser weapons. On the other hand, there is a greater potential of indiscriminate effects due to beam spreading. Because in many situations acoustic weapons would not offer radically improved options for military or police, in particular if opponents use ear protection, there may be a chance for preventive limits. Since acoustic weapons could come in many forms for different applications, and because blast weapons are widely used, such limits would have to be graduated and detailed.

INTRODUCTION[1]

Acoustic Weapons as Part of "Non-lethal" Weapons

Since the early 1990s there has been an increasing interest - mainly in the U.S. - in so-called non-lethal weapons (NLW) which are intended to disable equipment or personnel while avoiding or minimizing permanent and severe damage to humans. NLW are thought to provide new, additional options to apply military force under post-Cold War conditions, but they may also be used in a police context.[2] Whereas some foresee a military revolution and "war without death,"[3] most others predict or prescribe that NLW would just augment lethal weapons, arguing that in actual war both types would be used in sequence or in parallel.[4] However, there may be situations other than war when having more options of applying force below the threshold of killing could help to prevent or reduce deaths, e.g., in a police context (riots, hostage-taking) or in peace-keeping operations. A range of diverse technologies has been mentioned, among them lasers for blinding, high-power microwave pulses, caustic chemicals, microbes, glues, lubricants, and computer viruses.

Whereas at present it is mainly the U.S. that push research and development of these technologies,[5] a new qualitative arms race in several areas could ensue if they were deployed. There is also a danger of proliferation, which may "backfire" if such new weapons are used by opponents or terrorists.[6] Some concepts would flatly violate existing disarmament treaties, e.g., using microbes as anti-matériel weapons.[7] Others could endanger or violate norms of the international humanitarian law.[8] Thus, there are good reasons to take critical looks at NLW before agreeing to their development and deployment.

Such critical analyses have to consider scientific-technical, military-operational, and political aspects. To some extent, the latter two aspects depend on the first one. Well-founded analyses of the working of NLW, the transport/

propagation to a target, and the effects they would produce, are urgently required. This holds all the more, as the published sources are remarkably silent on scientific-technical detail. Military authorities or contractors involved in NLW research and development do not provide technical information.[9] There are also certain dangers that – absent reliable information – poorly founded views and promises by NLW proponents get more political weight than warranted, or that decisions are being made based on a narrow military viewpoint.

As one general example of such promises note the statement:[10] "The scientists involved in the development of these (NLW, J.A.) technologies know no limits, except funding and support. If they worked at it, they could eventually make it do whatever they needed it to do," a claim that neglects to take into account first, the laws of nature and second, the possibility of countermeasures by opponents.

Since NLW comprise many very different technologies, an in-depth analysis is needed for each type of weapon.[11] The present article presents an analysis of acoustic weapons, with an emphasis on low-frequency sound. Such weapons have been said to cause, on the one hand, disorientation, nausea, and pain without lasting effects. On the other hand, the possibility of serious organ damage and even death has been mentioned – thus the "non-lethal" label does not hold for all possible types and uses. Table 1 lists a few allegations concerning acoustic weapons. Because many of these are based on hearsay and not on publicly documented cases, they cannot be taken as reliable information, but rather as indicators of directions where independent analysis is needed.

Table 1: Selected examples of alleged properties, effects, and targets of acoustic weapons from the available literature; not often are sources given. Note that there are some inconsistencies, as, e.g., whether high or very low frequencies are used in "acoustic bullets" (refs. 18-21). In some cases one cannot avoid the impression that the respective author/s misunderstood something or mixed things up, as, e.g., with the plasma created by an acoustic bullet or with equalling non-diffracting with non-penetrating (ref. 18). [12] ARDEC: U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal NJ, U.S., LANL: Los Alamos National Laboratory, Los Alamos NM, U.S., SARA: Scientific Applications and Research, Huntington Beach CA, U.S.

Sound Source	**Effects**	**Targets**	**Ref.**
Infrasound	May affect labyrinths, vertigo, imbalance, etc.; resonances in inner organs, e.g., heart, with effects up to death	Riot control (British use in Northern Ireland)	13
Infrasound from non-linear superposition of two ultrasound beams (tested in Great Britain)	Intolerable sensations	Riot control	14
Infrasound	Incapacitation, disorientation, nausea, vomiting, bowel spasms; effect ceases when generator is turned off, no lingering physical damage	Crowd/riot control, psychological operations	15
Very low frequency noise	Disorientation, vomiting fits, bowel spasms, uncontrollable defecation	Enemy troops	16
Infrasound - tuned low frequency, high intensity	Anti-personnel: resonances in body cavities causing disturbances in organs, visual blurring, nausea - temporary discomfort to death. Anti-material: embrittlement or fatigue of metals, thermal damage or delamination of composites; against buildings: shattering of windows, localized earthquakes		17

Sound Source	Effects	Targets	Ref.
Infrasound from banks of very large speakers and high-power amplifiers not yet existing, requiring new cooling design and new materials	Discomfort, disorientation, nausea, vomiting	Hostage rescue, crowd/riot control, psychological operations	18
High-power, very low frequency acoustic beam weapon, being developed in conjunction with SARA, by ARDEC and LANL; phased-array setup allows smaller size, about 1 m^3 (on small vehicle); smaller later in the future	Discomfort like standing near large air horn (certain frequencies and intensities)	Protect U.S. overseas facilities (e.g., embassies), riot control	19
Very low frequency acoustic bullet, emitted from antenna dishes, being investigated at ARDEC		Offensive capability against personnel in bunkers or vehicles	20
High-power, very low frequency acoustic bullets from 1-2 m antenna dish	Incremental effects from discomfort to death		21
High-frequency, non-diffracting (i.e., non-penetrating) acoustic bullet creates plasma in front of target	Blunt-object trauma		19
Baseball-sized acoustic pulse, about 10 Hz, over hundreds of meters, developed in Russia	Selectable from non-lethal to lethal levels		22
"Deference tone" at intersection of two otherwise inaudible beams, developed in Russia			22

Some Historic Aspects of Acoustic Weapons

Whereas low-frequency sound was often used passively by armed forces to detect and locate artillery, nothing is known about actual weapon use by the military. Two infrasound review articles mention that there are indications that Great Britain and Japan had investigated this possibility, and then demonstrate that for *lethal* use over some distance unrealistically high source powers would be required.[23]

With respect to *non-lethal* use of low-frequency sound, already a 1969 book on riot control mentioned that the theory of using sound as a weapon had been discussed in many scientific articles (which, however, the present author cannot confirm), that super- and subsonic sound machines had been tested for riot control, and that these machines had generally turned out to be too costly, too cumbersome and too unfocused.[24] The only sound device discussed in some detail, the “Curdler” or “People Repeller” was said to emit shrieking, pulsating sound that, amplified by a 350-W amplifier, produced 120 dB at 10 m distance.[25]

In 1971 a short survey from the British Royal Military College of Science mentioned reducing resistance to interrogation, inducing stress in an enemy force, creating an infrasonic sound barrier and rapid demolition of enemy structures.[26] Somewhat later, the journal *New Scientist* - in the context of reporting on weapons used by the British Army against protesters in Northern Ireland - wrote about successful tests of the “squawk box,” a device said to emit two near-ultrasound frequencies (e.g., at 16.000 and 16.002 kHz) which would then combine in the ear to form a beat frequency of, e.g., 2 Hz, said to be intolerable.[27] The Ministry of Defence denied the existence of the device.[28] A later book assumed that it had never been fully developed.[29] (For a discussion of this possibility, see 5.1.2 below).

At the same period, there was a series of articles stating marked effects of infrasound such as dizziness and nausea at levels between 95 and 115 dB which other experimenters, however, could not confirm.[30]

U.S. forces used loud music to force M. Noriega out of his refuge in Panama in 1989.[31] Since such sound applications work rather by annoying than by physical damage, they will not be further discussed here.

Actual Developments

The US Army Armament Research, Development and Engineering Center (ARDEC) at the Picatinny Arsenal, New Jersey, is responsible for the Army effort in the Low Collateral Damage Munitions programme.[32] One project in low-frequency acoustics is a piston- or explosive-driven pulser forcing air into tubes to produce a high-power beam, to be applied against small enclosed volumes; another deals with the possibility of projecting a non-diffracting acoustic “bullet” from a 1-2 m antenna dish using high-frequency sound. Both were to be done by Scientific Applications and Research Associates (SARA) of Huntington Beach, California.[33] Similar projects seem to be underway in Russia: in a Center for the Testing of Devices with Non-Lethal Effects on Humans in Moscow, long-time U.S. NLW proponents J. and C. Morris were reportedly shown a device propelling a baseball-sized acoustic pulse of about 10 Hz over hundreds of meters, scalable up to lethal levels. Another principle was a “defference” (probably difference) tone produced at the intersection of two otherwise inaudible beams.[34] (For a discussion of acoustic bullets and generation of audible or infrasound from two ultrasound fields, see 5.1.3 and 5.1.2 below).

As with the U.S. projects, reliable public information is not available.

The most specific information available at present seems to be contained in the first few pages of a SARA report of 1996,as reported in a recent overview article:[35]

- With respect to effects on humans, some of the allegations are: Infrasound at 110-130 dB would cause intestinal pain and severe nausea. Extreme levels of annoyance or distraction would result from minutes of exposure to levels 90 to 120 dB at low frequencies (5 to 200 Hz), strong physical trauma and damage to tissues at 140-150 dB, and instantaneous blast-wave type trauma at above 170 dB (for an explanation of the level unit decibel see below). At low frequencies, resonances in the body would cause hemorrhage and spasms; in the mid-audio range (0.5-2.5 kHz) resonances in the air cavities of the body would cause nerve irritation, tissue trauma and heating; high audio and ultrasound frequencies (5 to 30 kHz) would cause heating up to lethal body temperatures, tissue burns, and dehydration; and at high(er?) frequencies or with short pulses bubbles would form from cavitation and micro-lesions in tissue would evolve.
- Under development are a non-lethal acoustic weapon for helicopter deployment (tunable 100 Hz to 10 kHz, range above 2 km, goal 10 km), a combustion-driven siren on a vehicle (multi-kilowatt power, infrasound), and an acoustic beam weapon for area denial for facilities housing weapons of mass destruction using a thermo-acoustic resonator, working at 20-340 Hz.
- Using combustion of chemical fuel, scaling up to megawatt average power levels would be possible, with fuel tank storage capability - at fixed sites - for a month or more.
- Acoustic weapons would be used for US embassies under siege, for crowd control, for barriers at perimeters or borders, for area denial or area attack, to incapacitate soldiers or workers.

It should be noted that several of the claims about effects do not stand critical appraisal, in particular for the infrasound and audio regions.[36] The same holds for a range of kilometers.[37] It seems that SARA have taken earlier allegations at face value without checking their correctness.[38]

In Germany, Daimler-Benz Aerospace (DASA), Munich, has done a detailed study of all kinds of non-lethal weapons for the Ministry of Defence in 1995. Whereas most of the descriptions of technologies and effects are sound, the section on acoustic weapons contains errors.[39] Recently, the German

Fraunhofer Institute for Chemical Technology was tasked to develop a prototype and test the deterring effect of strong sound.[40]

Goals of This Article

To my knowledge, acoustic weapons have not been the subject of detailed public scientific analysis. They were discussed in a section of a 1978 book and a 1994 conference contribution, both motivated by humanitarian-law concerns; these, however, are rather short and non-quantitative.[41] A recent article is significantly more comprehensive, but relies heavily on general statements from a firm engaged in developing acoustic weapons, the defence press, and military research and development institutions. The author calls for a "much more sophisticated and fuller understanding of the damage caused by high power acoustic beams" and asks the humanitarian-law community to involve itself in the assessment and debate.[42]

The present article is intended to contribute to that goal by presenting more, and more reliable, information, so that serious analysis of military-operational, humanitarian, disarmament, or other political aspects need not rely on incomplete or even obscure sources.[43]

This study is based on the open literature and my own theoretical analysis, without access to scientific-technical data gained in acoustic-weapons research and development and without original experiments. Something may have been overlooked; at some points speculation is unavoidable; and some questions will remain open, hopefully to be answered by future work.
The questions to be answered are the following:

- What are the effects of strong, in particular low-frequency, sound on humans?
- Is there a danger of permanent damage?
- What would be the properties of the sound sources (above all, size, mass, power requirement)?
- How, and how far, does strong sound propagate?
- Can we draw conclusions on the practical use by police or military?

The following subsection gives a few general remarks on acoustics. The major sections deal with effects of strong sound on humans, production of strong sound, protective measures, and therapy. Finally, preliminary conclusions are given. The appendix mentions, first, some properties of pressure waves in air. Second, allegations concerning acoustic weapons made in journalistic articles are analyzed.

General Remarks on Acoustics

In a broad sense, any variation of air pressure in time constitutes sound. For a sinusoidal time course, the number of repetitions per time unit is called the frequency, measured in Hertz = 1/second. Usually, the frequency region below 20 Hz is called infrasound, but this is not an absolute hearing limit - sounds with lower frequencies can be heard and otherwise perceived if the pressure is high enough. To prevent misunderstanding with the term "audible," in this article the range from 20 Hz to 20 kHz will be called "audio." The hearing, pain, and damage thresholds decrease with increasing frequency between a few Hz and 20-250 Hz (see figure 2 below); thus low-frequency effects will be much stronger at low audio frequencies than with infrasound proper. Therefore, despite the emphasis on infrasound in the journalistic articles, here the range from 1 to 250 Hz is denoted by "low frequency" and treated in common. For frequencies above 20 kHz, the usual term "ultrasound" will be used.

Pressure variations mean deviations from the average air pressure toward higher and lower values, denoted by over- and underpressure. Usually these deviations are much smaller than the air pressure; they are called sound pressure. Because sound pressure and intensity vary over many orders of magnitude, and because the human loudness sensation is approximately logarithmic, these physical quantities are often given as levels L in a logarithmic scale, in decibel units, where

$$L_p = 20\log(p_{rms}/p_{ref})\,dB \quad and \quad L_I = 10\log(I_{rms}/I_{ref})\,dB \qquad (1)$$

p_{rms} and I_{rms} are the respective root-mean-square values of sound pressure (deviation from static air pressure, measured in Pascal) and sound intensity (acoustic power per area, proportional to sound pressure squared, measured in Watt/square meter). A ten-fold increase in pressure means a hundred-fold increase in intensity and an increment of 20 dB in level. For the reference values, in acoustics usually

$$P_{ref} = 20\mu Pa \quad and \quad I_{ref} = 10^{-12} W/m^2 \qquad (2)$$

are chosen. These values are about the human hearing threshold at 1 kHz, close to the frequency of highest sensitivity; thus with equation (A-2) and an acoustic air impedance of $\rho_0 c_0 \sim 400$ kg/(m^{2}s) under normal conditions both levels, for pressure and intensity, are equal.[44] Levels will usually refer to these values in this article; frequency-weighted level scales incorporating human sensitivity, such as the dB(A), when used, will be denoted as such.

The most important properties of pressure waves in air are mentioned in appendix 1. For sound pressures which are not extremely strong - below maybe 100 Pa (level 134 dB), 0.1 % of normal pressure -, the effects can be described by linear equations. The sound speed is constant, and the superposition principle holds as, e.g., in optics (linear acoustics). At higher values, but still below atmospheric pressure, the increase of propagation speed with pressure becomes important, and waves become steeper as they propagate, but the underpressure is about the same as the overpressure and the propagation speed remains the same as with small amplitudes (non-linear acoustics, weak-shock formation). Such non-linear effects would be important in the conversion of frequencies that has been alleged to take place with acoustic weapons. If the overpressure is larger than the pressure at rest, as, e.g., with blast waves from explosions, the shock speed becomes much faster, and the underpressure can no longer be of equal amplitude (strong shock). It seems problematic to count a blast-wave weapon as an “acoustic” one, otherwise many types of explosive shells, bombs, or fuel-air explosives would come under the same heading.[45] However, for the sake of completeness, because of a smooth transition from one to the other, and because blast waves have been mentioned in this context,[46] strong shock is included into the present considerations.

Effects of Strong Sound on Humans[47]

Strong sound can temporarily or permanently reduce the hearing ability and affect the vestibular organ. At extreme levels, physical damage to organs of the ear can occur even with short exposure. At even higher levels, occurring practically only in overpressure pulses from explosions, other organs are injured, with the lung as the most sensitive one.

In this section, a few general properties of the ear and damage to it are described first. In the following parts, special emphasis is put on low frequencies because their effects are less known than in the audio region, and because they are mentioned in many publications on acoustic weapons. High-frequency audio sound and ultrasound are covered rather briefly. A special subsection treats shock waves, e.g., from explosive blasts.

Table 9 at the end of this section gives a simplified summary of the various effects in the different frequency ranges.

General Remarks on the Ear[48]

Hearing and Hearing Damage

In the human ear (figure 1), sound waves entering the ear canal set the eardrum into vibration. This motion is coupled by the three middle-ear ossicles to the oval window at the beginning of the labyrinth. The resulting pressure wave travelling in the cochlear perilymph bends the basilar membrane which separates the cochlea longitudinally into the scala vestibuli and the scala tympani; these two canals are connected at the cochlea tip, and the latter one leads back to the round window at the middle ear. The basilar membrane carries the organ of Corti the hair cells of which sense the deformation and relay this information via ganglion cells to the brain. The Eustachian tube connects the middle ear and the nasal cavity. Linked to the cochlea are the cavities and three semicircular canals of the vestibular organ which senses head motion and helps maintaining equilibrium.

The middle ear contains mechanisms that can reduce the amount of vibration coupled to the inner ear, thus defining the limits of hearing and reducing damage from strong sound. At very low frequencies, the Eustachian tube can provide pressure equalization. The aural reflex, which contracts muscles (m. tensor tympani and m. stapedius) in the middle ear about 0.2 s after the onset of strong noise, weakens the transmission of the ossicles. Due to the mechanical properties of the ossicles, frequencies above about 20 kHz are not transmitted.

After exposure to strong sound the auditory system usually becomes less sensitive; in other words the threshold of hearing is shifted to higher levels. Recovery is possible if the exposure is below frequency-dependent limits of sound level and duration, and if the following rest period is sufficient. This is called temporary threshold shift (TTS) and is usually measured 2 minutes after the noise ended. Up to TTS levels of about 40 dB, recovery is smooth and mostly finished within 16 hours. Beyond certain limits, recovery is incomplete and permanent threshold shifts (PTS), i.e., permanent hearing losses, remain. Because this so-called “noise-induced hearing damage” is somehow cumulative, exposure criteria have to include the duration and recovery time beside spectral composition and level.[50]

Whereas TTS can be studied with humans in experiments, for PTS one has to rely on people injured by accident, occupational noise or the like. The other method is to do animal experiments - the results of which of course can-

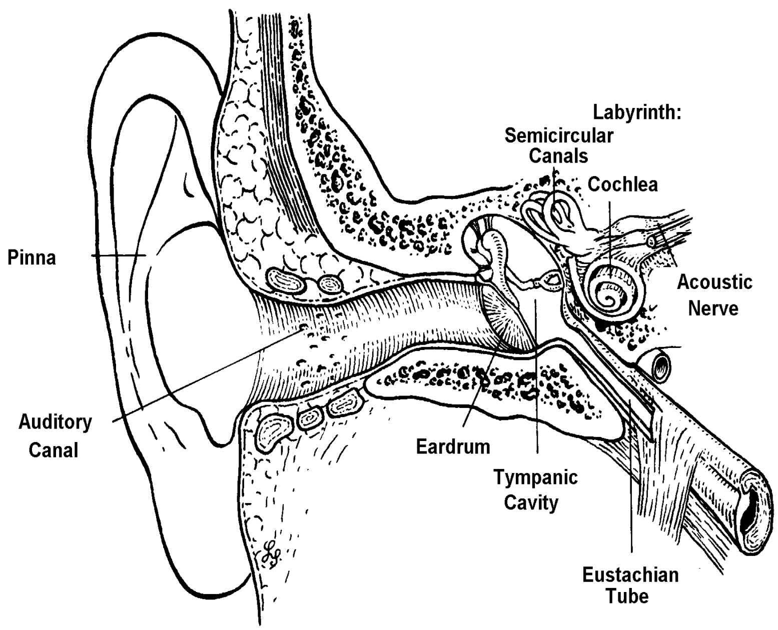

Figure 1: The human ear consists of three parts: external, middle, and inner ear. Sound waves reflected by the pinna and travelling in the auditory canal produce vibration of the eardrum (tympanic membrane). The three middle-ear ossicles (malleus, incus, and stapes) transfer this motion - increasing the pressure - to the oval window at the entrance of the labyrinth and to the perilymph inside. The resulting pressure wave travels into the cochlea, bending the basilar membrane which separates the cochlea longitudinally and carries the sensory hair cells. Their excitation is relayed to the brain by the acoustic nerve. Pressure equalization of the middle ear is possible via the Eustachian tube. The middle-ear muscles (not shown) can reduce the transmission of the ossicular chain. The second part of the labyrinth is the vestibular organ with its cavities and semicircular channels for sensing motion. (Modified from ref. 49, used by permission of authors and publisher; original copyright: Springer-Verlag).

not directly be applied to humans. As animal species for model systems, often chinchillas, guinea pigs, or cats are selected, thought to be more sensitive than humans; but also dogs, monkeys, and for blast waves sheep have been used.

Which noises will produce more PTS (for higher level and/or longer duration) can be predicted on the basis of the TTS. There are complicated schemes to quantitatively estimate PTS from noise via expected TTS, reasoning that the PTS after 20 years of near-daily exposure is about the same as the TTS after 8 hours. PTS is thought to be produced by mechanical and metabolic processes damaging the sensory hair cells on the basilar membrane of the cochlea. PTS – as well as TTS – is relatively variable between subjects. Usually, it develops first and strongest at 4 kHz, then spreading to lower and higher frequencies, relatively independent of the noise spectrum at the workplace. There is a considerable amount of literature on all aspects of hearing damage, such as measuring and documenting it, understanding the physiological mechanisms, estimating the risks quantitatively, recommending limits for preventive measures, considering acceptable damage, and percentages of people affected. Most concerns are on cumulative effects of many years of exposure as, e.g., in the workplace, where PTS has been found at levels below 80 dB(A), but usually it is the range from 80 to 105 dB(A) that matters. There is, however, also injury produced by one or a few short-term exposures to strong sound - this often comes under the name "acoustic trauma."[51] Its inner-ear effects range from some disarray of the hairs of the hair cells to complete destruction of the organ of Corti. Secondarily, ganglion cells and nerve fibres may degenerate.

Figure 2 shows the human hearing threshold and curves of equal perceived loudness from very low to high frequencies.[52] As can be seen, perceived loudness, measured in phones, increases about logarithmically with sound pressure at each frequency. Also drawn are thresholds for damage effects to the auditory system which are important for judging acoustic weapons:

- Thresholds of hearing hazard – above the first one there is a danger of permanent hearing loss under certain conditions – noise level, duration, number and schedule of exposures, variables of the individual. Close to the threshold, the duration may amount to several hours of daily exposure over many years. Above the second threshold, at 120 dB where discomfort begins, there is a high risk of hearing loss even for short and few exposures (except impulse sounds).

- Aural pain – this occurs above about 140 dB (200 Pa) throughout the audio region. However, in the infrasound range the threshold increases with falling frequencies to 160 and 170 dB (2 and 6 kPa). For static pressure, pain occurs above about 173 dB (9 kPa) of underpressure and about 177 dB (14 kPa) of overpressure. Pain is thought to occur when the mechanical limits of the middle-ear system are transcended, and it is not directly connected to sensitivity or hearing damage: damage can occur without pain and vice versa. However, under normal conditions exposure should be stopped when pain is felt.

- Eardrum rupture – the threshold is at about 160 dB (2 kPa) in the audio region. For a step to a static overpressure the threshold is at 186-188 dB

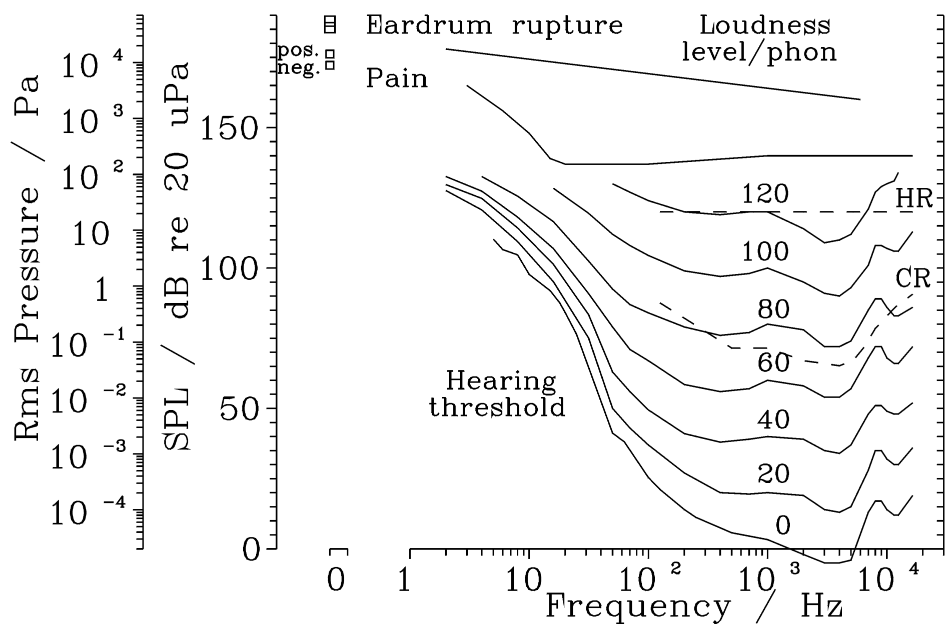

Figure 2: Threshold of hearing (corresponding to 0 phone), curves of equal perceived loudness for 20, 40, 60, 80, 100, and 120 phones, rms sound pressure (logarithmic scale) and its level versus frequency. The threshold values are for binaural hearing of pure tones; monaural perception thresholds are higher. Also given are the thresholds of conditional (CR) and high (HR) risk of permanent hearing loss (dashed), of aural pain and of eardrum rupture. The high-risk threshold is also valid for the feeling of discomfort; the threshold for tickle sensation is slightly below the one for pain. Especially for eardrum rupture, the threshold is only roughly known. On the left, pain and eardrum rupture thresholds are shown for static pressure. For pain, the values for over- (pos.) and underpressure (neg.) are slightly different. Note that normal atmospheric pressure is 101 kPa.[53]

(42- 55 kPa peak). Even though membrane ruptures usually heal, damage to the middle and inner ear may remain. However, rupture serves as a kind of fuse, reducing the pressure transmitted to the inner ear, and thus the potentially permanent inner-ear damage.

Vestibular System

The vestibular system of the inner ear contains cavities (utricle and saccule) with sensors for linear accelerations and three semicircular channels for sensing angular accelerations. The vestibular system causes – via several, mostly sub-conscious channels in the central nervous system – eye movements and postural changes, and provides perception of motion and orientation. The vestibular system is one of the sensor modalities responsible for motion sickness (the other two, the visual and somatosensory systems, are less relevant in the present context).

The liquids (endolymph and perilymph) in the vestibular organs are connected to those in the spiral cochlea. Thus, acoustic stimulation of the balance organs is possible in principle, and this would be the mechanism for the alleged production of vertigo and nausea by infrasound. Effects and thresholds observed with humans and animals are discussed below for the different frequency ranges.

Effects of Low-Frequency Sound

In the 1960s and 1970s there was a wave of ascribing exaggerated effects to infrasound, not only in the general press.[54] Much of this was anecdotal. In some cases, effects observed in one laboratory could not be reproduced in another. One reason may be production of harmonics in test systems.

Hearing Threshold and Loudness Perception at Low Frequencies

Hearing does not abruptly stop below 20 Hz. As careful measurements have shown, with high enough sound pressure the ear can register infrasound down to about 1 Hz. However, below about 50 Hz the hearing threshold increases steeply with falling frequency, as evident in figure 2.[55] At lower frequencies, the equal-loudness curves lie much closer; this means that loudness perception increases much faster with sound pressure level than at higher frequencies. Also the pain threshold is closer to the hearing threshold at low frequencies.

High-Intensity Effects of Low-Frequency Sound on Ear and Hearing

The human auditory system seems to be relatively tolerant of low-frequency exposure, especially with infrasound where even at very high levels only some TTS and no PTS occurs (table 2). Infrasound even reduces TTS from high-frequency noise because (quasi-)static loading of the middle ear reduces its transmission to the inner ear. It is likely that PTS observed, e.g., in people exposed to low-frequency noise at the workplace is mainly due to higher frequencies also present.

Table 2: Auditory effects of low frequency sound in humans. Note that chinchillas, much more sensitive in the audible range, showed clear middle and inner ear damage after exposures to frequencies between 1 and 30 Hz at levels 150-172 dB.

Frequency /Hz	**Level / dB**	**Duration**	**Effect**
<1 - 20	125-171	minutes	often TTS at audio frequencies, recovery within 1/2 hr
3 or 23	130	1 h	no TTS
Low audible	90	many hours	TTS, recovery after up to 2 days
≤ 40	140-150	0.5-2 min	no PTS
Simulated airbag inflation:			
Infrasound part (c. 5 Hz)	165 peak	0.4 s	no TTS
High-frequency part (0.5-1 kHz)	153 rms	0.4 s	TTS 5-8 dB at 1.5-12 kHz
Both parts together	c. 170 peak	0.4 s	TTS 2-3 dB at 1.5-12 kHz
Sonic boom (mainly 2-20 Hz)	162-171 peak	seconds	no PTS

Of course, threshold shifts are not immediately felt by the individual and are thus irrelevant as weapons effects, at least as far as the weapon designers and users are concerned. More relevant will be a pressure sensation, which develops at about 130 dB, independent of frequency. Even more impressive will be pain in the ear which sets in between 135 and 162 dB depending on frequency, see figure 2. The human eardrum ruptures above 42-55 kPa static pressure change (186-189 dB). Since for audio frequencies, the threshold is assumed to be well over 160 dB (2 kPa), infrasound should lie somewhere in between.[57]

High-Intensity Effects of Low-Frequency Sound on the Vestibular System

Vestibular excitation can be measured by reflexively produced eye movements (nystagmus) or, with humans, by performance in balancing tests. Neither in animals nor in humans were effects observed from infrasound at 130 to 172 dB. Thus, the vertigo and nausea effects in the journalistic articles ascribed to intense infrasound cannot be confirmed. On the other hand, low audio frequencies of 50-100 Hz at 150 to 155 dB caused mild nausea and giddiness.

High-Intensity Effects of Low-Frequency Sound on the Respiratory Organs

Strong infrasound of 0.5 Hz can act like artificial respiration. Exposure to sonic booms (main energy in the infrasound region) between 154 dB (1.0 kPa) and 171 dB (6.9 kPa peak) did not lead to adverse effects on the human respiratory system.

In the low audio frequency region below 50 Hz, exposure to levels up to 150 dB (0.63 kPa) caused chest-wall vibration and some respiratory-rhythm changes in human subjects, together with sensations of hypopharyngeal fullness (gagging); these effects were felt as unpleasant, but clearly tolerable. Between 50 and 100 Hz, however, subjective tolerance was reached and exposure discontinued at 150 to 155 dB (0.63 to 1.1 kPa); respiration-related effects included subcostal discomfort, coughing, severe substernal pressure, choking respiration, and hypopharyngeal discomfort.[58]

Other High-Intensity Effects of Low-Frequency Sound

Several other effects were observed during exposure to intense low-frequency (30 to 100 Hz) sound at levels around 150 dB. Among these were increased pulse rates, cutaneous flushing, salivation and pain on swallowing. The visual field vibrated and acuity was reduced. Subjects showed marked fatigue after exposure. On the other hand, brief infrasound had no effect on visual acuity, motor tasks and speech production.

Vibration Considerations

It is sometimes maintained that infrasound sets organs in motion similarly to external vibration applied to the body. Whereas there are similarities, there are also important differences.

For vertical vibratory excitation of a standing or sitting human body, below 2 Hz the body moves as a whole. Above, amplification by resonances occurs with frequencies depending on body parts, individuals, and posture. A main resonance is at about 5 Hz where greatest discomfort is caused; the reason is in-phase movement of all organs in the abdominal cavity with consequent variation of the lung volume and chest wall.[59]

Conditions are different when slow air pressure variations impinge on the human body. At low frequencies where the body dimensions are smaller than the wavelength, e.g., above 2 m for frequencies below 170 Hz, the same momentary pressure applies everywhere, and the tissue behaves as a viscoelastic fluid with much lower compressibility than air.[60] This produces some vibration, but due to the large impedance mismatch nearly all energy is reflected. The exceptions are where enclosed air volumes render the body surface softer, as in the ear, where 90 % of the impinging energy is absorbed, or at the lungs, where the chest wall or the abdomen can move more easily if external pressure/force is applied. Because the external pressure simultaneously produces air flow through the trachea into and out of the lungs, the inner pressure counteracts the chest wall and abdomen movements. The system acts much more stiffly than with unidirectional vibratory excitation, and the resonance (with the highest velocities per sound pressure and thus highest tissue strains) is at 40 to 60 Hz instead of one tenth of that value.

Effects of High-Intensity High-Frequency Audio Sound

Effects on Ear and Hearing

PTS is mainly seen and studied with occupational exposure over a decade and more, from weighted levels of below 80 dB(A) to usually less than 120 dB(A). The sensitivity to TTS and PTS follows roughly the loudness contours. In the present context, however, the questions relate to short exposures at potentially higher levels.

Concerning the danger of permanent damage from a single or few exposures (acoustic trauma), there are understandably not many experimental studies with humans. In order to estimate expected effects one can evaluate related TTS experiments, use damage criteria gained from the parallelism between TTS and PTS, and draw cautious conclusions from animal experiments. Table 3 shows that short exposures at high levels need not produce PTS in humans. Table 4 shows the results of PTS experiments on animals.

Table 3: Auditory effects of high-frequency audio sound on humans. At higher audio frequencies, humans are much less susceptible than around 1 kHz.

Frequency / kHz	**Level / dB**	**Duration**	**TTS**	**PTS**	**Remarks**
0.1, 1, 2, 4	110, 120, 130	1 - 64 min	strongest at 4 kHz, much less at 1 and 2 kHz, even less at 0.5 kHz; recovery from 60 dB TTS in up to 5 days	no evidence	
0.25 - 5.6	up to > 140	many seconds		obviously none	testing for tickle and pain thresholds
Broadband noise (0.5-1 kHz, simulated airbag inflation)	153 rms	0.4 s	TTS 4-8 dB at 1.5-12 kHz, vanished after minutes	none	young, healthy men
Jet afterburner noise	> 140	seconds at a time		no consistent PTS after several months	flight-deck/ airfield ground personnel
9 - 15	140 - 156	5 min	TTS at exposure frequencies and half of those, fast recovery	none	

Table 4: PTS and physiological damage produced by high-frequency audio sound in animals. With the cat experiments, at all frequencies a 10-dB increase marked the transition from minimal to severe destruction in the cochlea.

Animal	Frequency / kHz	Level / dB	Duration	PTS	Physiological damage
Chinchilla		~ 120	~ 1 h		damage to hair cells, etc.
Guinea pig	0.19 -8.0	135-140	few minutes		severe hair cell injury
		>40	few minutes		organ of Corti destroyed at respective most affected site
Cat	0.125	150	4 h	none	hair cell losses in general-paralell to functional deficiencies
		153-158	4 h	partially/ fully deaf	
	1.0	120	1 h	none	
		130	1 h	55 dB at 2kHz	
		140	1 h	deaf at all frequen-cies	
	2.0	140	1 h	deaf at ≥ 2 kHz	
	4.0	135	1 h	none	
		140	1 h	60 dB at 4 kHz	

Acoustic trauma for short exposures occurs above some critical combination of level and duration which corresponds to a kind of “elastic limit” of the organ of Corti. In chinchilla and guinea pig experiments extensive damage was about the same if the duration times the intensity squared was constant, i.e., for each 5 dB level increase the duration has to be divided by 10. Assuming the same law to hold for humans, and taking the critical value separating some hearing loss from acoustic trauma from guinea pigs which are closer to the human sensitivity, e.g., 7 minutes of 135 dB, one would arrive at alternative combinations of 40 s exposure to 140 dB, 4 seconds to 145 dB, and 0.4 seconds to 150 dB.[61] Thus it seems advisable to assume that a singular exposure at the pain threshold in the audio range (140 dB) will become dangerous, i.e., produce marked PTS in the majority of the people affected, after about half a minute, and above that at progressively shorter intervals.

Eardrum rupture at high audio frequencies is expected above a threshold of over 160 dB (2 kPa).[62]

Non-Auditory Effects of High-Intensity High-Frequency Audio Sound

Vestibular responses in humans are elicited by audio sound above about 125 dB. At levels about 140 dB near jet engines, an equilibrium disturbance was felt at critical rotation rates. Though these authors quote several oral communications about similar effects and though they themselves have been quoted often, it seems that the conditions and causes have not been analyzed thoroughly.[63] High-level effects in animals range from eye movements to severe lesions in the vestibular organs. With high-frequency audio sound, no adverse effects on respiration are to be expected, since the pressure changes occur much too fast for significant motion of either body walls and organs, or the air in the trachea. However, resonances in the opened mouth, the nasal cavities or sinuses may produce a sense of touch or tickling above 120 dB.

At levels of 160 dB and higher, heating becomes relevant. Whereas absorption is small on naked skin due to the impedance mismatch, it becomes strong wherever strong friction impedes the air movement, as in textiles, hair, fur, or narrow ducts. Since levels above 140 dB in the high-frequency audio region are extremely rare, and people in the workplace need to be protected because of their ears in the first place, it seems that auditory as well as non-auditory injury due to such noise has practically not been described.[64]

Effects of High-Intensity Ultrasound

Around 1950, there was increased talk and fear of "ultrasonic sickness" connected with symptoms of headache, nausea, fatigue etc. experienced by personnel working in the vicinity of the newly-introduced jet aircraft. Later, similar complaints came from people working with washers and other ultrasound equipment in industry. It seems, however, that these effects were rather caused by high- and sometimes low-frequency audio noise simultaneously present.

Auditory Effects of Strong Ultrasound

The upper threshold of hearing varies between subjects and decreases with age. Whereas using bone conduction aural effects can be elicited, airborne ultrasound (above 20 kHz) cannot be heard by nearly all people and does not have a marked effect on the human ear. When subjects were exposed to the high audio frequency of 17 kHz and ultrasound ones of 21 to 37 kHz at levels as high as 148 to 154 dB, there was some TTS at the first sub-harmonics (half frequency) and, for the higher two excitation frequencies, also at the second ones. These shifts vanished rapidly and no PTS remained.

Considering the non-linear production of sub-harmonics observed in electrophysiological recordings from guinea pigs and chinchillas, an extension of damage-risk criteria to the ultrasound region was proposed with a limit of 110 dB.

Non-Auditory Effects of Strong Ultrasound

In an analysis of ultrasonic washers and drills, in the vicinity of which workers had experienced fatigue, headaches, tinnitus, and nausea, it turned out that there were considerable levels at audible frequencies as well which were identified as the probable causes. No vestibular effects were reported with the TTS tests at up to 154 dB. Respiratory effects are again not to be expected because of the fast pressure changes.

At extreme levels, close to a siren of maximum 160-165 dB, tickling in mouth and nose was observed with ultrasound as with high-frequency audio sound. For such levels, as with high audio frequencies, heating will occur mostly in narrow passages and other places of high friction.[65] Above, heating will be felt at naked skin as well.

Impulse-Noise and Blast-Wave Effects

Impulse noise occurs with shooting or in industry, see table 5. Here it is particularly noteworthy that overpressures produced by toy weapons or firecrackers are in the same range as those of real rifles or those experienced by artillery gun crews. The durations and thus pulse energies may differ, though.

In explosions, overpressures can reach many times the normal atmospheric pressure. The pressure time course is usually that of a strong-shock wave, i.e., a fast increase and then a slower, more or less linear decrease via a negative phase to ambient pressure. However, whenever there are walls, reverberations will occur, increasing the duration and energy to which the ear is exposed.

Table 5: Peak pressure values of several sources of impulse noise, measured at (potential) ear positions (of worker, marksman or gun crew). Note that normal atmospheric pressure is 101 kPa.

Source	**Peak overpressure / kPa**	**Peak level / dB**
Drop forge	0.11	135
Shooting bolts into walls, 80 cm	0.63	150
8 toy pistol types, 50 cm	0.63-2.0	150-160
3 toy paper-cap gun types, 30 cm	0.89	153
8 firecracker types, 3 m	0.063-63	130-190
Sonic boom low-flying aircraft (N wave)	2.4-6.9	162-171
Pistol	5.0	168
Rifle	1.7	159
4 rifles	1.78-8.43	159-173
Automatic rifle	7.2	171
Field cannon 105	50.3	188.0
17 Pdr. T/A gun	54	188.6
3 inch mortar short	58	189.2

Auditory Effects of Impulse Noise

Exposure to impulse noise causes similar effects as continuous noise: at lower levels there is a TTS, first at 4-6 kHz. For repeated exposure over long time, this may develop into PTS and deteriorate by involving a wider frequency band. At higher levels, permanent damage may ensue even from one or a few events. With impulses the individual susceptibility varies even more than with continuous noise. This is demonstrated in the first entries of table 6 which shows TTS and PTS data from humans. Ear pain may occur already at

0.36 kPa overpressure (145 dB), however, there are cases of no pain even when both eardrums were ruptured. Table 7 gives results from animal experiments. With impulse noise, TTS often increased in the first hours after exposure.

Table 6: Auditory effects of impulse noise and blast waves on humans.

Peak level / dB	Pulse duration	Number of pulses	TTS	PTS	Remarks
140	2 ms	75	40 dB at 4 kHz	none	most sensitive subject
155	2 ms	75	< 40 dB at 4 kHz	none	least sensitive subject
159	rifle shots		30 - 80, recovery in up to 6 days	none	marksman position
189	gun shots		30 - 80, recovery in up to 6 days	none	gun-crew position
180-183	blank shot		30 - 80, recovery in up to 6 days	none	ear near rifle muzzle
186-189	3" mortar	first shot	max. 75 dB at 5.8 kHz		monaural exposure - pain, tinnitus
		second shot after 80 min.	recovery up to 5.8 kHz in 2 months	50 dB at 8.2 and 9.7 kHz	eardrum rupture, bleeding
Fire-cracker 0.5 m from ear		1		60-80 dB at ≥ 3 kHz	male student
150-160 at 0.5 m	toy weapons		with 2 - 5 % of population (600)	with 2.5 % of population, mean 29 dB at 4 kHz	village festival in India
130-190 at 3 m	firecrackers		with 2 - 5 % of population (600)	with 2.5 % of population, mean 29 dB at 4 kHz	village festival in India
162-171	40-400 ms	many		none	sonic-boom N waves

Table 7: TTS, PTS, and physiological damage produced by impulse noise in animals

Animal	Peak level / dB	Number of pulses	Pulse duration	TTS	PTS	Physiological damage
Rhesus monkey	168	2 10 - 20 more	60 µs pos., 100 ms neg. press.	33 dB median at 14 kHz	some up to 15 dB median	 local or extended loss of hair cells
Chinchilla	131, 135, 139, 147	1, 10, 100	~ 5 ms (reverberant)	15 - 90 dB mean	0-45 dB mean	hair cell losses roughly parallel to PTS
Guinea pig	153	500	35 µs pos. press. (toy cap gun)			local hair cell damage as from 125-130 dB of 2 kHz for 4 h

When considering safe exposures to impulse noise, the peak level, duration, spectral content, pause interval, and number of impulses have to be taken into account. As a criterion for short impulses, a peak level of 162 dB (2.5 kPa) has been given.[66]

Concerning higher overpressures from explosions, experiences exist with humans who suffered from war, bombings, and, rarely, industry accidents; experiments have been done on preparations from human cadavers and with animals. The overpressure threshold for eardrum rupture has been given as 35 kPa (peak level 185 dB) (table 8). Only at shorter durations will the inertia of the eardrum and middle ear play a role to withstand higher pressures.

Among the victims of bomb blasts there is a high incidence of eardrum rupture. Fracture or displacement of the middle-ear ossicles is rare. Hearing loss, pain, tinnitus, and vertigo are the most common symptoms; the latter may often have to do with direct head injury. Smaller eardrum ruptures heal to a large extent. The other symptoms usually decrease over time as well, but often a permanent hearing loss remains.

In animals, eardrum rupture from blasts has been studied for decades, using atmospheric nuclear explosions, shock tubes, or live ammunition. Peak overpressures for dogs, sheep, pigs, and monkeys are similar to those of humans.

Table 8: Severe damage to humans by strong-shock waves, e.g., from blasts (fast pressure rise, then about linear decrease with the duration given). For each effect, three pressures are shown: the threshold below which the effect will not occur, the level where the damage is expected to affect 50% of the exposed persons, and the 100% level. The pressures are the peak effective overpressures (free-field if parallel, free-field plus dynamic if perpendicular incidence, and reflected if in front of a large surface). Due to variability and - in the case of humans - non-availability of experiments, ranges are given instead of fixed values. For repeated exposure, damage thresholds are lower. For shorter durations, thresholds are higher. Note that normal atmospheric pressure is 101 kPa corresponding to 194 dB peak level.

Damage	Threshold overpressure / kPa	Overpressure for 50 % incidence / kPa	Overpressure for 100 % incidence / kPa
Eardrum rupture			
fast rising, duration 3 and 400 ms	35	105	
slowly rising/static	42-55	~150	
Lung rupture		"severe"	"severe"
duration 3 ms	260-340	680	680
duration 400 ms	83-103	260	260
Death			
duration 3 ms	770-1100	1100-1500	1500-2100
duration 400 ms	260-360	360-500	500-690

Non-Auditory Effects of Impulse Noise

Vestibular effects of impulse noise were observed with humans as well as with animals. Guinea pigs exposed to rifle shots showed not only severe damage in the cochlear organ of Corti, but also lesions in the vestibular end organs, even though the animals had not shown marked signs of vestibular disturbance. With soldiers suffering from hearing loss due to exposure to firearms as well as with bomb victims, vestibular damage was found. There are, however, several ways of compensating for a loss of vestibular-organ sensitivity.

The organ second most sensitive to blast is the lung with the upper respiratory tract. As a marker for the threshold of unsafe levels, the occurrence of petechiae (bleeding from very small lesions of capillaries, harmless and self-healing) in the respiratory tract has been proposed; these occur at tens of kilopascals (about 180 dB peak level). With higher pressures, however, large hemorrhages form not only in the tracheae, but also in the lung, due to contusion. Tissue tears may lead to large-scale bleeding or edema in the lung and to air emboli which eventually can cause death by suffocation or obstruction of blood vessels. With sheep exposed to shock waves between 86 and 159 kPa (193-198 dB) and about 5 ms duration, lung injury ranged from moderate to strong, but still sub-lethal. Estimates of overpressures for human lung damage and death are given in table 8.[67]

Table 9: Simplified summary of the threshold sound levels in dB for various effects relevant for acoustic weapons in the different frequency ranges (rms levels) and for blast waves (peak levels). Note that the levels are approximate, that the effects change smoothly with frequency and depend on duration, and that there is wide invidual variability. For details, see the respective subsections in the text and the references given there. k: kilo (1000).

Range	**Frequency / Hz**	**Ear pain**	**PTS from short exposure**	**Eardrum rupture**	**Transient vestibular effects**	**Respiratory organs**
Infrasound	1 - 20	160 .. 140 (1 .. 20 Hz)	none up to 170	>170	none up to 170	none up to 170
Low audio	20 - 250	135 - 140	none up to 150	160	150 mild nausea	150 intolerable sensations
High audio	250 - 8 k	140	120 .. 135 .. 150 1 h .. 7 min .. 0.4 s strongest at 1-4 kHz	160	140 slight equilibrium disturbance	140 tickling in mouth etc. 160 heating
Very high audio/ ultrasound	8 k - 20 k/ > 20 k	140	none up to 156	?	none up to 154	140 tickling in mouth etc. 160 heating
Blast wave	-	145	150 - 160	185	160	200 lung rupture 210 death

Production of Strong Sound

Whereas sources of audio sound are well known, this is much less so for sources of low-frequency sound, and in particular of infrasound, which occurs at surprisingly high levels in everyday life. Thus several low-frequency sources are described first. Then, strong sources potentially usable for weapons are discussed.

Sources of Low-Frequency Sound

Infrasound proper is produced naturally by sea waves, avalanches, wind turbulence in mountains, volcanic eruptions, earthquakes, etc. Whereas such waves are only very slightly absorbed and - augmented by high reflection at the ground and a refracting channel in the atmosphere - can travel thousands of kilometers, the pressures and frequencies are such that humans do not hear them, and all the more are not negatively affected. Thunder has time-varying spectral peaks from infrasound to low-audio sound and can of course be heard. Wind gusts can produce quite high dynamic pressures; from the expression for the dynamic pressure

$$p_d = \rho_0 v^2 / 2 \tag{3}$$

(the air density at sea level is ρ_0=1.2 kg/m^3), it follows that for a peak wind speed of v =10 m/s the peak pressure is 65 Pa, corresponding to a level of 130 dB; with gale speed of 40 m/s, 1.04 kPa or 154 dB results. That such pressure fluctuations do not produce pain is due to the fact that wind varies on a time scale of seconds, i.e., with frequencies below or about 1 Hz.

Human-produced infrasound can have comparable or even higher amplitudes. Diving into water of density ρ_W to a depth of Δh=2 m increases the pressure according to

$$\Delta\rho = \rho_W \, g \, \Delta h \tag{4}$$

(g=9.81 m/s^2 is the gravity acceleration at sea level) by Δp=19.6 kPa (level 180 dB) within a second or so.[68] Blowing into another's ear can produce 170 dB. Even running produces considerable amplitudes; applying (4) with an rms head motion amplitude of Δh=0.1 m and the density of air ρ_0 results in 1.3 Pa (level 96 dB).

Whereas these examples have dominant frequencies around or below 1 Hz, sounds from jet aircraft, rockets or airbag inflation reach up to and into the audio range.

Lower levels are produced by wind turbines, air conditioning and ventilation, and inside cars or trucks; opening a window produces a marked increase in the infrasound region. In industry, low-frequency sound is produced by compressors, crushers, furnaces etc. In the engine room of ships, high levels have been found.

Finally, blast waves need to be mentioned. Their overpressure amplitude can be arbitrarily high, whereas the following negative wave is of course limited to the negative atmospheric pressure (101 kPa at sea level).[69]

In order to test effects of low-frequency sound, special test equipment has been developed. For testing only the ears, low-frequency 15-W 30-cm loudspeakers have been tightly fitted with a plate; a hole connected this to the ear defender of a headset. Thus, levels up to 140 dB (400 Pa) were achieved.[70]

In order to test whole-body exposure, several test chambers of 1-2 m^3 volume have been built. Here also sealing is necessary to prevent pressure equalization with the outside at wave-lengths larger than the chamber dimension. One chamber working with six 0.46-m loudspeakers achieved 140 dB (200 Pa).[71] However, speakers provide only limited travel (1 cm or less) of their membranes. Stronger pressure variation is possible with pistons driven, e.g., hydraulically. For example, the Dynamic Pressure Chamber built at the Wright-Patterson Air Force Base in Ohio, U.S., has one piston of 0.46 and another of 1.83 m diameter and 12 cm maximum travel; this can achieve pressure levels of 172 dB (8.0 kPa) from 0.5 to 10 Hz, falling to 158 dB (1.6 kPa) at 30 Hz.[72] Note that the same piston, when working into free air at 10 Hz, is equivalent to a spherical source of only 82 Pa rms pressure (132 dB) at 1 m radius; at 1 Hz, 0.82 Pa (92 dB) would remain, with 6 dB decrease per doubling of distance.[73] This demonstrates the difficulty of producing low-frequency sound of high intensity in free air, and shows why tight closure of the test chambers is required.

Table 10 lists several sources of low-frequency sound.

Table 10: Sources of low-frequency sound, dominant frequency range, and sound pressure level at typical distance (o.c.: own calculations).

Source	Dominant frequency range / Hz	Sound pressure level / dB	Ref.
Geophysical	< 0.01-10	54 - 104	74
Thunder at 1 km	< 4 - 125	< 114	75
Wind fluctuations	~ 1	up to > 160	o.c.
Running	< 2	95	76
Blowing into another's ear	~ 0.5	170	76
Diving to 2 m of water	~ 1	180	76
Wind turbine, 150 m downwind	2 - 10	80	77
Ventilation/air conditioning	1 - 20	60 - 90	77
Industry	5 - 100	70 - 110	78
In car (window closed)	5 - 100	100	78
In car (window open)	1 - 30	120	78
Jet aircraft (underneath flight path at airport)	10 - sev. 1000	135	79
Jet engine with afterburner (at runway margin)	20 - 800	148	80
Large rocket, crew compartment	10 - 2000	135	81
Large rocket at 1.6 km	1 - 200	130	82
Sonic booms	1 - 100	120 - 160	83
Airbag inflation	~ 5 / 500 - 1000	170	84
Ship engine room		133	85
Blast wave	< 1 - 100	unlimited	
Loudspeaker headset	1 - 200	146	70
Whole-body chamber, loudspeakers	2 - 100	140	71
Whole-body chamber, piston	0.5 - 10/30	172/158	72

Acoustic Sources Potentially Usable for Weapons

Strong sounds can of course be produced by *loudspeakers* connected to amplifiers.[86] Providing enough electrical power requires a generator or heavy batteries, and achieving very high levels outdoors needs very large banks of speakers. Typical maximum electrical powers fed to one speaker are a few 100 W, of which only 1 or 2 per cent are converted to acoustic power, due to the membrane-air impedance mismatch.[87] Better efficiencies (10 to 50 %) are possible with (exponential or other) horns in front of the speaker which also improve directivity. For low frequency, horns have to be large.[88]

The main advantage of loudspeakers, namely their capability to emit a broad range of frequencies without large distortion, may not be needed for acoustical weapons, however. If just loud noise is to be produced, there are simpler possibilities, e.g., a siren or a whistle. Table 11 lists such sources with their properties.

In a *siren*, an air flow is periodically opened and blocked by a rotor the holes of which pass holes in a stator. Whereas early types had efficiencies of 1 - 2 per cent, already in 1941 a model was built which produced about 37 kW acoustical power (at 460 Hz) from 52 kW air flow power, i.e., with about 70% efficiency. This device - with its 71 kW and 15 kW combustion engines for the compressor and rotor, respectively - was mounted on a small truck; the six exponential horns of combined diameter 0.71 m provided a direction pattern with half-pressure angle of about 40° from the axis, about fitting to diffraction of the 0.75-m wavelength. With pressure levels above 170 dB in the horns, the wooden horns used first were destroyed during the first 5-minute test and had to be replaced by ones made of steel. With propagation in open terrain and a 1.42 m wide extension horn, an approximate $1/r$ decrease of the maximum pressure – due to spherical propagation – was observed to more than 500 m distance; on-axis levels were 137 dB, about the pain threshold for the unprotected ear, at 30 m and 127 dB at 100 m.[89]

Whereas somewhat more compact siren designs at the same power level are certainly possible, the input power required, the limits on flow and pressure within the siren and the size of the horns for impedance matching and achieving directivity for frequencies up to hundreds of Hertz result in sizes of 1 meter and more – the larger, the deeper the frequency. The device will require at least a pickup truck for mobility.

Sirens can also be used to produce high-frequency sound, up to the ultrasonic region. For example, with a device of 0.3 m size and 25 kg mass (without compressor) working with 200 kPa overpressure and an air flow of 0.1 m^3/s, levels of 160-165 dB with more than 2 kW of acoustic power were produced at

3 to 20 kHz, at an efficiency of 20%.[90] Another device produced about 160 dB at low ultrasonic frequencies and more than 140 dB at 150 kHz; higher levels were possible in the audio range.[91]

The siren principle – modulation of an air flow by opening and closing of holes – can also be used to produce sound of arbitrary waveforms. One example of such an infrasound-capable siren speaker is the Mobile Acoustic Source System (MOAS) which the National Center for Physical Acoustics at the University of Mississippi built for the Battlefield Environment Directorate of the U.S. Army Research Laboratory.[92] This unique system can provide 20 kW of acoustic power through an exponential horn of 17 m length and 2.3 m maximum diameter; the cutoff frequency is 10 Hz. It is mounted together with the 115 kW Diesel compressor on a telescoping semi-trailor. Here, a cylinder with slits on the circumference is moved electrodynamically past corresponding slits on a fixed cylinder, thus the air stream can be modulated by the current in the driving voice coil. From 63 to 500 Hz the on-axis frequency response is essentially flat, about 152 dB at 1 m radius for an equivalent point source; below, it falls to about 130 dB at 1 m at 10 Hz. From the first number, one can compute that the on-axis level decreases below 137 dB, about the pain threshold for unprotected ears, at 5.6 m from the assumed point source (located in the centre of the horn opening), i.e., already in the immediate vicinity.[93] The 120 dB range is 40 m. For infrasound, the increasing pain threshold and decreasing horn efficiency combine to prevent ear pain even close to the mouth, again demonstrating the difficulty of producing very high low-frequency amplitudes in free air. The main purpose of the MOAS is to test atmospheric propagation over many kilometers; another one is to simulate vehicle noise. The strong non-linearity in the device does not hamper these applications.

Periodic strong low-frequency air vibration can also be produced aerodynamically, by non-linear production of turbulence interacting with resonators, as in organ pipes and *whistles*. In the Galton whistle an air flow from an annular orifice hits a sharp circular edge inside of which is a cylindrical resonating volume. This whistle type has been used to produce frequencies from infrasound to ultrasound, mainly depending on the resonator size. Some variation of resonance frequency is possible by adjusting the length of the cavity. In the region 40 to 200 Hz, other whistle types have produced higher acoustic powers, up to the kilowatts range, with sizes on the order of 1 meter.[94] Infrasound would require much larger resonators (frequency scales inversely with resonator length) and compressor powers (scaling with air flow area).

For high audio frequencies and ultrasound, Galton whistles are less powerful than Hartmann whistles, where the annular orifice is replaced by an open nozzle. These produce frequencies from several kHz to about 120 kHz; modified versions have achieved up to about 2 kW at 4 to 8 kHz at efficiencies of up to 30%. Using a parabolic reflector of 200 mm diameter, a beam width (full width at half maximum pressure) of about 30° was achieved. For ultrasound, using multi-whistles up to 600 W were achieved with about 10 and 33 kHz.[95]

In order to produce high-power ultrasound in air, *piezoelectric transducers* vibrating larger disks can be used. With one design, a stepped-thickness disk to achieve in-phase emission despite nodal circles, sound levels above 160 dB (2 kPa) were reached in front of the 20 cm diameter disk; it had to be water-cooled to avoid breaking. The efficiency was about 80%, the sound power up to about 200 W. The resonance bandwidth was only a few Hz. The half-intensity beam width was 5° (about fitting to linear diffraction), and the on-axis level had decreased to 150 dB (0.63 kPa) at 1 m distance.[96] Thus, at 10 m 130 dB (63 Pa) would result in the case of linear propagation, with an additional attenuation by 8 dB (factor 0.4 in pressure) due to absorption. However, shock would set in at about 0.1 m, increasing the losses.[97] In an experiment, with a level at the source of 153 dB (0.89 kPa) only about 123 dB (28 Pa) remained at 5.7 m distance.[98]

Finally, there is the possibility to produce a shock pulse by an *explosive blast*. In the case of spherical propagation even a sizable charge of 1 kg TNT may produce ear pain to about 200 m, whereas injury or fatality is expected only to a few meters.[99] The latter use would of course represent a traditional weapon and damage mechanism (note that in many weapons the lethality radius against persons is increased beyond the one due to blast by packing shrapnel around the explosive). Utilizing the ear pain mechanism with a spherically expanding shock would be problematic for several reasons. With regard to the effect, because the user needs to be protected, which is done best by distance, the charge is usually thrown before it is ignited. Since each charge would produce just one pulse, it could be necessary to repeat the use often. Seen from a viewpoint of humanitarian law or of non-lethality, on the other hand, there is the danger that the aiming is not exact and the charge explodes too close to someone, causing permanent injury or death. There may be an exception with very small charges, which could be used to cause surprise and confusion, especially within closed rooms. But here the visual effects of the accompanying light flash may even be more important, and such weapons are already in use. With very small charges (grams to tens of grams), there is also the principal possibility of a rifle-like weapon shooting explosive bullets to some distance (see below). If the explosion does not occur in free air, but in some open cavity or tube, resonance can intensify a certain frequency range.

A new perspective on shock-wave weapons would exist if it were possible to direct the shock, avoiding spherical distribution of the energy released, and so having only to deal with, e.g., 1/r decrease with distance – due to shock heating of the air – in the theoretical case of a beam of constant width. In the absence of published data, some speculation is justified for a preliminary analysis. Conceivably, the spherically expanding shock wave from an explosion could be caught in surrounding tubes, the other ends of which would be bundled in parallel in a circular, approximately planar transmitting area. By suitable bends, the tube lengths would vary in such a way that the individual shock waves would arrive about simultaneously at the openings, there combining to a common large shock wave which would start with an approximately planar front. This would be equivalent to a homogeneous layer of explosive on the emitting area ignited nearly simultaneously everywhere. The explosive layer could of course also be formed by, e.g., gasoline mixed with air, sprayed from small nozzles, ignited by an array of spark plugs. The main question here is how far the beam radius would remain the same, or how soon spherical spreading – with the accompanying shock $1/r^3$ decrease with distance – would set in. However, strong shock waves expanding into free air suffer from diffraction from the beginning, even though modified by the pressure dependence of speed.[100] Thus, it seems that although some concentration of the energy into a cone may be possible, spherical propagation will hold from a distance several times the source diameter. More definite statements require a detailed study.

One can also speculate what would happen if such explosions - with initially planar, bounded wave fronts – were produced repeatedly. In analogy with combustion engines, where many thousands of ignitions can occur per minute in each cylinder, frequencies of 100 Hz are conceivable with liquid fuel, with micromechanical valves etc. potentially much higher values. Of course, cooling, withstanding the overpressure pulse, and the recoil will present formidable, but solvable, engineering problems. Estimates show that megawatt power,[101] source levels around 180 dB (tens of kPa pressure, still marginally in the weak-shock region with nearly symmetric waveforms) are possible with a fuel consumption of tens of grams per second, comparable to a tank engine.[102]

After the first shock, each sufficient one would propagate in already heated gas with a correspondingly higher speed. Thus, later shocks would continuously reach and replenish the first front. As there would be some decrease of pressure and temperature away from the beam axis, following wave fronts would become more forward-dented and would suffer more from diffraction loss away from the axis. Quantitative estimates of the overpressure decrease with the distance and angle from the axis require much more clarification by the developers of such systems and/or a detailed theoretical study.[103]

In order to overcome the amplitude decrease with distance, one can also use a *small source* which is moved close to the target. The principle is exemplified by exploding or whistling firecrackers. The latter could contain a whistle or siren, driven by a pressurized-gas container or a gas generator (as, e.g., in an airbag), and could work for many tens of seconds up to minutes, depending on size.

With a mass of hundreds of grams, both types could be thrown by hand or shot by a rifle; heavier "sound grenades" could be shot by a larger (air) gun.[104]

Table 11: Strong sound sources potentially usable for acoustic weapons. The values given are typical or apply to a specific device (notional for the hypothetical repetitive-blast device). k: kilo (1000); o.c.: own calculations. Note that in case of very high levels close to the source, at high audible or ultrasound frequencies non-linear effects will lead to strong absorption and fast decrease of pressure level with distance.

Source	Diameter of emitting area / m	Frequency / Hz	Acoustic Power / kW	Sound pressure level / dB	At distance / m	Ref.
Large siren	1.4	200 - 600	37	137	30	89
Small siren	0.3	3 k -20 k	2	165	close	90 91
Large air-flow-modulation speaker	2.3	10 - 500	20	126	27	92
Giant whistle	0.2	40 - 200	several	160	close	94
Hartmann whistle	0.2	4 k - 8 k 20 k	2 0.6	160	close	95
Piezoelectric transducer with disk	0.2	20 k	0.2	160	close	96 98
Explosive blast	1	< 1 - 100	unlimited	unlimited		
Hypothetical repetitive blast	1	100	1000	180	close	o.c.

In conclusion, it is possible to construct strong sources of low-frequency sound which can be tuned to some extent, or which can deliver arbitrary waveforms, with efficiencies between 10% and 70%. Beam widening roughly corresponds to diffraction. Resonators, air flow limits, horns for directivity, and power requirements, all drive the size of such sources with their auxiliary equipment into the range of 1 meter and more, and the mass to several hundred kilograms and more.

Higher audio-frequency and ultrasound sources could be somewhat smaller, but due to their power requirements no great reduction of the total system size seems possible. (Compare the sizes of the required engines, electrical generators or compressors with those of commercial gasoline-engine AC generators of 1 to 5 kW.)

Explosive-driven sources can produce blast waves, probably also with repetition at low audio frequencies. Megawatt powers seem achievable, again with source sizes on the order of 1 meter.

Hand-held acoustic weapons of pistol or rifle size with ranges of tens of meters can be excluded almost certainly. The only exception would be a small whistling or exploding “sound grenade” thrown or shot to within a few meters from a target.

Protection from High-Intensity Sound

The sound pressure acting on the eardrum can be reduced by earplugs which are inserted into the external ear canal, or by ear muffs enclosing the outer ear. Whereas both types can provide attenuation from 15 to 45 dB at higher frequencies (500 Hz and above, including ultrasound), earmuffs are less efficient at low frequencies (250 Hz and below); at some infrasound frequencies, they even may amplify levels. Here, earplugs are better; those of the premolded or user-formable type attenuate by 10 to 30 dB at low frequencies. The best low-frequency protection is provided by earplugs made of slow-recovery, closed-cell foam; these can reach 35 dB if inserted deeply. Combinations of earplugs and earmuffs are advisable for protection against impulsive peak sound levels of 160 dB and above. Combining an earphone with a sound-absorbing helmet can achieve 30-50 dB attenuation from 0.8 to 7 kHz. Much stronger attenuation at the external ear is not useful because sound reaches the inner ear also by bone and tissue conduction.[105]

Protection against whole-body exposure can principally be provided by enclosures that are sufficiently stiff so that they are not easily vibrationally excited transmitting sound to the inside, or by linings with sound-absorbing, e.g., porous material. For jet engine technicians, protective suits exist.[106] The absorption mechanism loses its value with low frequencies, however – when the lining becomes thinner than about one-fourth wavelength (e.g., 0.34 m for 250 Hz), the absorption decreases with decreasing frequency.[107] For very high impinging levels at high frequencies, heating in the absorptive material may present a problem, but in the present context this is mostly theoretical because of the strong decrease with distance.

An armored vehicle, if completely closed, should provide considerable protection against low-frequency sound. A normal road vehicle, on the other hand, is neither air-tight nor are windows or panels stiff enough not to transmit impinging low-frequency pressure variations. Similarly, low-frequency sound may enter buildings via slits or closed windows. If the frequency corresponds to a room resonance,[108] internal pressures by far exceeding the impinging ones can develop. Utilizing this effect requires a variable-frequency source and some on-site modelling and/or experimentation. It is conceivable that during resonance build-up windows burst – due to their large areas at levels below the human pain threshold – diminishing the resonance effect again.

At higher frequencies, on the other hand, walls, windows, sheet metal and the like can provide substantial attenuation.

Therapy of Acoustic and Blast Trauma

Here only a few indications will be given.[109] Some immediate effects of overexposure to sound may simply vanish with time – from minutes to months – such as hearing loss, tinnitus, pain, or vertigo. Some, however, may remain permanently. These are probably caused by inner-ear damage, e.g., to hair cells on the basilar membrane in the cochlea, or by similar effects in the vestibular system. Such damage seems to grow for a few hours after acoustic trauma, which may have to do with reduced blood supply. Thus, drugs furthering blood circulation are often given. There are conflicting studies on the success of such treatment.[110]

Since further exposure to strong noise increases the damage and interferes with a healing process, achieving quiet at an injured ear as fast as possible (e.g., by an earplug) is an important part of therapy.[111]

Tympanic-membrane ruptures produced by bombings healed spontaneously in 80-90% of the cases. Operations closing the membrane are mainly required when the perforations are larger than one third. Fracture or displacement of middle-ear ossicles occur more rarely and indicate much more severe blast damage; these require much more complicated surgery.[112]

Whereas there are cases when nearly full recovery of hearing occurred even after ruptures of both eardrums, it is more likely that PTS - of moderate to severe extent – ensues.[113] Therapy cannot do much about that; providing hearing aids may be the main form of help after the fact. In case of near-deafness, providing a cochlear or even brain-stem implant for direct electrical stimulation of sensory or nerve cells - an expensive treatment – may restore significant hearing and speech-perception abilities.[114] Prevention, e.g., by ear protection, is the only reliable way to avoid permanent hearing losses.[115]

Conclusions

Judging acoustic weapons is particularly complicated because there are so many facets. The potential effects range from mere annoyance via temporary worsening of hearing to physiological damage of the ear, and in the extreme even of other organs, up to death. The criteria will also differ according to the intended context and scenario of use; the spectrum extends from close-range protection of fixed installations to mobile systems, on the one hand for law enforcement, on the other hand for armed conflict. Lack of official information on development projects and unfounded allegations on properties and effects of acoustic weapons make judgement even more difficult.

Rather than trying to provide a complete judgement for all possible weapons types and use options, this article aims at providing facts that further the debate and eventually help to arrive at responsible decisions on how to deal with acoustic weapons. This section summarizes the main results of the study, and ends with a few general remarks.

Effects on Humans

Contrary to several articles in the defence press, high-power infrasound has no profound effect on humans. The pain threshold is higher than in the audio range, and there is no hard evidence for the alleged effects on inner organs, on the vestibular system, for vomiting, or uncontrolled defecation up to levels of 170 dB or more.

Throughout the audio region (20-20,000 Hz), annoyance can occur already at levels far below bodily discomfort, in particular if the sounds are disliked and/or continue for a long time. This may produce the intended effects in specific situations, e.g., a siege of a building occupied by criminals. Because usually no lasting damage would result, there is no reason for concern under humanitarian aspects.

The situation changes at higher levels, where discomfort starts at about 120 dB and pain in the ears occurs above about 140 dB. As a consequence of intense sound, at first a reversible deterioration of hearing occurs (temporary threshold shift). Depending on level, duration, frequency, and individual susceptibility, however, already short exposures at levels above, say, 135 dB can produce lasting damage of hearing (permanent threshold shift). Such damage need not be sensed immediately by the victim; the deterioration may become known only later. It is mainly located in the inner ear. The eardrum ruptures at about 160 dB; even though it may heal, permanent hearing loss may remain.

With low audio frequencies (50-100 Hz), intolerable sensations mainly in the chest can be produced – even with the ears protected – but need 150 dB and more.

At medium to high audio frequencies, some disturbance of the equilibrium is possible above about 140 dB for unprotected ears. At even higher levels, tickling sensations and heating may occur in air-filled cavities, e.g., of the nose and mouth.

High audio frequencies (above 10 kHz) produce less threshold shift, and at ultrasound the ear is essentially untouched if levels are below 140 dB. In these frequency ranges heating of air cavities, of textiles or hair may become important above about 160 dB.

Early therapy may lead to some improvement after acoustic trauma. However, permanent hearing loss, once occurred, cannot really be reversed, leaving hearing aids and cochlear implants as the main means of reducing the consequences.

Shock waves from explosive blasts – for which the name "acoustic" is questionable – can have various effects. At moderately high levels (up to about 140 dB), there is temporary hearing loss, which can turn into permanent one at higher values. Above 185 dB eardrums begin to rupture. At even higher levels (about 200 dB, overpressure already 3 times the atmospheric pressure), lungs begin to rupture, and above about 210 dB some deaths will occur.

Potential Sources of Strong Sound

Loudspeakers are not very efficient in producing strong sound, unless coupled with horns. Higher levels are more easily achieved with sirens producing single tones of variable frequency, powered, e.g., by combustion engines. At low frequencies sound powers of tens of kilowatts with a source level of 170 dB have been achieved; in the high audio and ultrasound range the figure is a few kilowatts at 160 dB. With a siren-type speaker low-frequency sound of arbitrary waveform can be produced at similar powers and pressure levels. With whistles, again mostly tonal sound is produced; at low frequencies, tens of kilowatts should be possible, at high audio frequencies several kilowatts, and in the ultrasound region around 1 kilowatt.

Explosive charges produce a blast wave the overpressure of which (at constant distance) scales linearly with the energy released; thus there is practically no upper limit at close range. A new type of source would result if explosions do not occur one at a time, but in fast sequence, with frequencies, e.g., in the low audio range. Here, megawatt acoustic power and 180 dB source level seem achievable in principle.

For nearly all source types mentioned, a typical size would be one meter or more. This holds for the source proper with its emitting area as well as for the associated power supply, e.g., a combustion engine. Rifle-like hand-hold acoustic weapons are only conceivable with ammunition for bangs or whistling; all other sources will be fixed, or will need a vehicle, helicopter or the like as a carrier.

Production of strong infrasound by non-linear superposition of two ultrasound beams is not realistic.

Propagation Problems

Whereas it is possible to achieve annoying, painful or injurious sound pressures for all source types mentioned – explosive blasts can even kill - if the target person is close to the source, there are great difficulties or unsurmountable problems when such levels are to be achieved at a distance.

The first obstacle is diffraction. Waves emitted from a source immediately diverge spherically if the wavelength is larger than the source; i.e., the power is spread over an area increasing with distance, and consequently the intensity and sound pressure decrease with distance. For source sizes on the order of one meter, this holds for frequencies below a few hundred Hertz. “Beams of infrasound” have no credibility. But even at higher frequencies with shorter wavelengths, where focusing or a beam of constant width can be achieved up to a certain distance, eventually spherical spreading will take over as well.

The second problem follows from the non-linear properties of the air. Whenever the sound pressure is as high as required for marked immediate effects, the wave crests move faster than the troughs, converting the wave into saw-tooth form after some distance. The ensuing shock fronts dissipate the wave energy much more strongly, so that the sound pressure decreases with the inverse of the distance, even for a plane wave without beam spreading, and more strongly in case of divergence. In the case of spherical blast waves, the decrease is by the cube of the inverse distance as long as the overpressure is larger than the normal atmospheric pressure.

Shock forms earlier and the associated energy losses become stronger with increasing frequency; thus, even if diffraction did not significantly reduce the sound pressure at a distance for some high enough frequency, shock-wave losses would then decrease the pressure from its initially high level along the beam. How far a given level can be projected depends on many details, such as source size, frequency, the form of the starting wave front, humidity of the air, intended level at the target, but as a rule of thumb one can state that projecting really high levels (say, above 140 dB) to more than 50 m does not seem feasible with meter-size sources.

Only with single blast waves produced by sizeable explosive charges (above 0.1 kg TNT) can shock overpressures transcend such levels at such distances. Because for impulses the human tolerance is higher, and because of the steep decrease with distance, much higher overpressures with the capability for lung rupture and death would hold at closer range.

I am not aware of a plausible mechanism for an alleged "basketball-size acoustic bullet" that could be even lethal over several hundred meters; clarifying or reliably refuting this allegation needs further study.

The case is different if strong acoustic waves are set up indoors, where the power is kept in place by reverberation from the walls. Achieving high levels will be particularly effective at room resonances. Direct coupling – e.g., through ventilation ducts – would be most efficient; next could be application of sound pressure via closely fitting tubes pressed against windows. Radiating a sound from a distance would provide the worst coupling, but may suffice to set up resonance vibration under certain conditions.

Further Study

There are a few areas where clarification or more detailed scientific-technical studies would be helpful. The more important issues are:

- quantitative aspects of the propagation of bounded beams of shocked waves (weak and strong shock);
- the working principle and specifications of a possible multi-explosion blast wave source; and
- the possibility of "diffraction-free" propagation of high-power acoustic pulses over considerable distances ("acoustic bullets"), in particular using vortex rings.

General Remarks

As with other types of "non-lethal" weapons, with acoustic weapons there are the problems of dosage and susceptibility varying among individuals. Exposed to the same sound level, sensitive persons may suffer from permanent hearing loss whereas for others the threshold shift is just temporary.

Impressive effects on the sense of equilibrium or the respiratory tract occur only at sound levels which pose an immediate danger of permanent hearing damage. Therefore, the promise by acoustic-weapons proponents of “no lingering damage” could only be implemented by fairly drastic limits, say, a sound level of no more than 120 dB at anybody's ear. This, however, would forego many of the hoped-for effects of acoustic weapons.

Because protection of the ears can be quite efficient throughout all frequencies, it would certainly be used by armed forces, organized militias and bands, at least after the first experience with acoustic-weapons use by an opponent. But since protection is so simple and easily available, it would probably also soon be used by “normal” people in demonstrations, etc.

Considering aspects of international humanitarian law, a complete analysis needs yet to be done. At the present stage, a few preliminary thoughts seem justified.

Acoustic weapons are different from the recently banned blinding laser weapons in several respects:

- The argument that 80-90% of the human sensory input is provided by the eye can obviously not be transferred to the ear; thus an argument on unnecessary suffering cannot be made on a similar basis as with blinding weapons.[116]
- Physiological injury to the ear from blast is common with conventional weapons.
- Even with ruptured eardrums, healing or at least improvement of hearing is possible.
- Hearing aids and implants are available, whereas comparable aids for the visual system do not really exist.

Thus, the case for a preventive ban under aspects of the international law of warfare is much less clear-cut here than with blinding lasers.

On the other hand, acoustic weapons bear a larger danger of indiscriminate effects, even though only at shorter range. Several types of acoustic weapons would be difficult to direct at only one person, all the more at one part of a person's body, because diffraction produces wave spreading. Thus, in several conceivable situations non-combatants or by-standers would be affected. As long as effects are temporary, or permanent effects are slight, this may be acceptable in certain circumstances.

At fixed installations, even sound sources capable of afflicting considerable lasting damage at close range might not meet strong objections, since on approach people would hear the sound and then feel pain and could in most situations withdraw voluntarily. However, if in a crowd pressing from behind, this may be impossible, so that one could demand non-damaging pressure levels (below, say, 120 dB) at the physical barrier protecting an installation.

Mobile acoustic weapons capable of producing permanent damage in a radius of, say, 10 or 20 m, would be much more problematic, especially in a law-enforcement context. One could probably not rely on the weapon users to keep certain limits; if to be obeyed at all, they would have to be built into the systems (e.g., in the form of absolute upper limits of power, or limits on actual power and duration depending on target distance, for targets within rooms special precautions would be needed).

The International Committee of the Red Cross has proposed four criteria for judging when design-dependent, foreseeable effects of weapons would constitute superfluous injury and unnecessary suffering. The first criterion is fulfilled if the weapon causes a "specific disease, specific abnormal physiological state, specific abnormal psychological state, specific and permanent disability or specific disfigurement."[117] Taken in this generality, certain acoustic weapons would fall under this rubric.

In sum, acoustic weapons would clearly not be the wonder weapons as sometimes advertised. Their use in armed conflict or for law enforcement would raise important issues concerning unnecessary suffering, protection of outsiders, and proportionality. One can conceive of special situations where acoustic weapons could add options for the application of legitimate force in a more humane way, possibly, e.g., in a hostage situation. However, the effects would be less dramatic than reported, especially on prepared opponents, whose own capability to inflict damage would not be reduced markedly. Thus the interest of armed forces and police in such weapons may turn out to be lower than their proponents would like.

This might mean that a determined attempt of the humanitarian-international-law community to preventively ban certain types of acoustic weapons may promise success. Because of the large variety of potential weapon types, of the effects on humans, and because of the large range of sound intensity potentially involved, for this purpose, clear definitions and criteria would be needed. One approach might, e.g., demand a limit of 120 dB at any publicly accessible point in the case of fixed strong sources. Mobile acoustic weapons could be banned – or limited to very low numbers for specific police uses – if they could produce more than, say, 130 dB at 5 m distance. Limits could also include the frequency-dependent human auditory sensitivity and be stricter in the range from 0.5 to 6 kHz. Such limits would aim at guaranteeing markedly less damage than usually afflicted with conventional fire weapons in armed conflict; thus general acceptance could become a problem if the discussion were limited to the law of warfare proper.

A more general approach similar to the one taken for the ban on blinding laser weapons – banning weapons specifically designed to render people permanently deaf – seems less sensible here, since that is not the main goal of present acoustic-weapon development, and deafening at short range could readily occur as a collateral effect of weapons designed for producing only temporary effects at larger distance. An even more general ban on deafening as a method of warfare, is unrealistic in view of the multitude of blast weapons in the arsenals of armed forces.

Because of the ease of protection, it may turn out that armed conflict will be the least relevant scenario, and that other operations, e.g., for crowd control, will be more realistic. Thus, considerations on bans or limits should take law-enforcement and other uses of acoustic weapons into their view from the beginning.

These arguments show that detailed deliberations are needed in order to arrive at a sensible course of action. It is hoped that this article contributes to that debate.

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Appendix 1: Pressure Waves in Air[118]

Linear Acoustics[119]

In the air pressure variations produced at a source propagate as sound waves. The exact wave equation is non-linear; however, for small variations, e.g., sound pressure below about 0.001 times static pressure, i.e., below 100 Pa (level < 134 dB), the pressure-volume curve of air can be replaced by its tangent and the equation linearized. In this case of linear acoustics, the sound speed is c_0=343 m/s at P_0=101 kPa static pressure and T_0=20 °C temperature, with density ρ_0=1.20 kg/m^3.

The sound pressure p is the deviation from the static pressure P_0. In order to estimate it for a simple source one can use the assumption of a monopole (i.e., a breathing sphere) emitting spherical waves in the open. If v_{rms} is the root-mean-square (rms) surface velocity of the sinusoidal vibration, the rms sound pressure – at distance r from the centre in the far field – becomes

$$p_{rms}(r) = \rho_0 \; c_0 \; k \; A \; v_{rms}/(4\pi r) \qquad \text{(A-1)}$$

where $k=2\pi/\lambda$ is the wavenumber, $\lambda=c_0/\nu$ the wavelength, ν the frequency. The rms intensity, i.e., the rms power per area transported with the wave, is

$$I_{rms}(r) = p^2_{rms}(r)/(\rho_0 \; c_0) \qquad \text{(A-2)}$$

the product $Z_0=\rho_0 c_0$ is called the impedance of free air. The intensity decreases with $1/r^2$ since the rms pressure decreases with $1/r$. The total power P_{rms} emitted is the integral over the full sphere at r,

$$P_{rms} = 4\pi r^2 I_{rms}(r) \qquad \text{(A-3)}$$

which is constant absent other losses.

If the wave field is not spherically symmetric, but confined to some cone of solid angle Ω, the intensity in that cone will be higher by $4\pi/\Omega$, and the pressure by the square root of that. If the source is a piston of radius a in an infinite, hard baffle, vibrating with rms velocity v_{rms} and frequency ν, then the rms pressure at distance r and angle ϑ in the far field is

$$p_{rms}(r, \vartheta) = \frac{\rho_0 c_0}{4\pi r} k 2 v_{rms} \pi a^2 \frac{2 J_1((ka)\sin\vartheta)}{(ka)\sin\vartheta} \qquad \text{(A-4)}$$

The Bessel function expression $2 J_1(x)/x$ is close to 1 from x=0 to about $\pi/2$. Comparison with (A-1) shows that on the axis (ϑ=0) the sound pressure is twice the one from a simple spherical source of equal surface area or volume flow rate, the intensity is four times stronger, due to the reflection at the baffle, or the expansion into a half-space. If the baffle is removed and the piston conceived to move in the mouth of a pipe,[120] the factor 2, or 4 for intensity, would vanish, the pipe end would act on the axis like a simple source of equal area or volume flow rate.[121] When the wavelength λ is longer than $2\pi a$, the circumference of the piston, the argument of the Bessel function term is below

$\pi/2$ even for $\vartheta = \pi/2$, the second fraction in (A-4) is 1, i.e., the sound pressure is essentially the same in all directions, including along the baffle or even – if $\lambda \geq 4\pi a$ backward for the case of the pipe. This means that in order to achieve directed emission for low frequencies, very large transmitting areas would be required, e.g., already for $\nu = 50$ Hz ($\lambda = 6.8$ m) a radius a clearly above 1.1 m is needed.

Transmitting a sound wave of sufficiently high frequency predominantly into a certain cone can be achieved by a horn with reflecting walls in front of the source, and enclosing the source at the back.[122] Due to its increasing cross section, it acts as an impedance transformer and can increase the efficiency of sound generation, e.g., from 1 - 2 % for a direct loudspeaker to 10 - 50 %.[123]
If parallel waves of constant intensity are emitted from a circular area, in the far field the innermost Fraunhofer diffraction spot is limited by the angle ϕ_1 of the first null of the Bessel function in (A-4):

$$\sin\varphi_1 = 1.22\lambda / D \tag{A-5}$$

where D is the diameter of the antenna. If the expression on the right is larger than 1, there is no null at all.

The intensity on the axis is

$$I_{max}(r) = P\pi D^2 / (4\lambda^2 r^2) \tag{A-6}$$

In the case of outdoors sound propagation, modifications apply due to several effects, most of which are small for the distances (10 to 100 m) considered here and are neglected for the simple estimates of the present assessment. However, some are difficult to assess in a given situation and thus add a significant amount of unpredictability for the use of acoustic weapons beyond about 50 m.

Non-Linear Acoustics - Weak-Shock Regime[124]

If the perturbations due to an acoustic wave are no longer very small compared to the static values, one has to consider the fact that the speed of propagation is no longer constant; it increases with pressure, density or particle velocity. Thus, regions of higher compression move faster, and regions of lower density more slowly, than the normal sound speed. This means that the wave form, even if sinusoidal at the start, becomes distorted (figure A.1 a). Relative to the zero crossings, the pressure peaks move forward and the troughs backward, finally forming a saw-tooth-like wave where at a given point in space there arrives first a positive pressure jump and then a linear decrease to the negative sound pressure minimum, repeated periodically (figure A.1 b). This

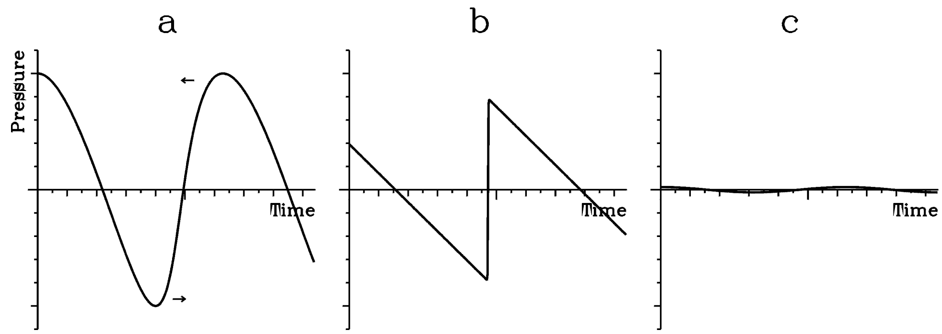

Figure A.1: Wave forms of an originally harmonic wave before and after shock formation. In the first stage (a), pressure peaks move faster and troughs more slowly, deforming the wave as it propagates. In the second stage, a rounded saw-tooth wave forms with strong dissipation in the shock front (b). The front becomes thicker and the amplitude weaker until finally a small sinusoidal wave remains (c). (Plotted vs. the space coordinate in propagation direction, the waves move to the right.)

can also be described as the successive build-up of harmonics of the original frequency (for an ideal saw-tooth wave, the amplitude of the n-th harmonic is proportional to $1/n$). Whereas dissipative losses in the medium are not important in the first build-up region, they increase strongly as soon as the shock front has been formed. During this second stage the amplitude and the non-linear distortion is slowly reduced, until the pressure becomes so low that linear propagation prevails again (figure A.1 c).

The details are complicated. For a plane wave, the rms sound pressure of a plane wave stays essentially constant during the first phase. After shock formation it decreases approximately as the inverse of the distance – note that this decrease holds for infinitely extended wavefronts and is not due to geometrical spreading. This phase ends with a low saturation amplitude which does not depend on the starting value. In the third phase, exponential attenuation prevails.

For spherical waves, the growth of the non-linear disturbance is accelerated in case of convergence, and decelerated for divergent waves, because the amplitude increases/decreases with radius r. If for a divergent wave shock occurs at all, the amplitude decrease is faster than with $1/r$; shock ceases at a certain radius.

In case of bounded waves (beams), the amplitude at some distance depends on the relative contribution of non-linear versus diffraction effects. Quantitative statements require detailed studies.[125]

Non-Linear Acoustics – Production of Difference Frequency, Demodulation[126]

If two waves of different angular frequencies ω_1, ω_2 propagate in a non-linear medium, the superposition principle no longer holds and combination frequencies $n\omega_1+m\omega_2$ (*n*, *m* integer) are generally produced. In particular in the present case, the difference $\Omega=\omega_1-\omega_2$ of two about equal angular frequencies may be interesting, because the former, due to its low value, would be much less absorbed by the air than the latter ones. Also the beam widening by diffraction would be much lower.

Superposition of two waves of similar frequency at first produces a variation in amplitude with the frequency difference, similar to an amplitude-modulated wave. In case of plane waves, the modulation- or difference-frequency-wave amplitude p_Ω will at first increase linearly with distance. After shock formation, however, it will saturate to a constant, with linear dependence on original amplitude p_0

$$p_\Omega = \pi m \Omega p_0 / (4\omega) \qquad \text{(A-7)}$$

($m \leq 1$ is the degree of modulation). This holds for a triangular wave and is correct except a constant factor for an originally sinusoidal one too, analogously for the difference frequency. (A-7) means that the sound pressure of the low-frequency wave is always lower than the original wave starting pressure by a factor Ω/ω, which is much smaller than unity under the assumptions made above.

Strong-Shock Regime[127]

In strong shock, as produced by an *explosive blast*, the overpressure is markedly above normal atmospheric pressure. A following underpressure pulse is limited to the atmospheric pressure, of course. Because of the high overpressure, the shock front moves with a velocity clearly above the sound speed. At any given distance, a fast overpressure jump occurs first, followed by a slower decrease to normal pressure, possibly via an under-pressure phase. After passage of the shock wave, the gas remains at elevated temperature and decreased density. The maximum overpressure scales approximately linearly with the energy and for three-dimensional propagation decreases approximately with the inverse cube of the distance. As soon as the overpressure falls below atmospheric pressure, transition to weak-shock, and finally linear, propagation with the usual sound velocity, and inverse-distance times exponential amplitude decrease, takes place.

Figure A.2 shows several quantities for explosions of 0.1 and 1 kg TNT in free air at sea level. Figure A.2 a shows the shock overpressure. The transition from the r^{-3} (strong-shock) to the r^{-1} (weak-shock/linear-propagation) dependence is seen around a distance of 3 and 7 m, at overpressures around one-third the normal pressure. It is interesting that even with 1 kg, a considerable amount of explosive – maybe ten times of that in a hand grenade – the threshold for eardrum rupture (about 35 kPa, see 2.5) is crossed at less than 5 m. On the other hand, the peak level is higher than 145 dB (0.36 kPa) where most subjects had felt pain in laboratory experiments,[128] to about 200 m.

Figure A.2 b shows the duration of the positive-overpressure part of the shock wave. It is obvious that for small chemical explosions the pulse durations – at applicable distances – are on the order of milliseconds, thus in table 8 the damage thresholds for the short times apply.

For such short waves, the body is very quickly immersed in the same overpressure from all sides, and a sizeable net force is mainly exerted by the dynamic-pressure drag of the moving air behind the shock. Figure A.2 c shows the approximate dynamic impulse per area for unity drag coefficient.

A strong-shock wave suffers from diffraction as well, but with a modification in that the propagation speed depends on the local pressure. For an extended plane or spherical wave, this mechanism provides for some stabilization of the shock front: should a backward bulge develop at some part, confluence of the power there would accelerate that part again, and vice versa. However, shocks emanating from the open end of a tube show immediate widening and propagation even in the backward direction along the outer side of the tube.

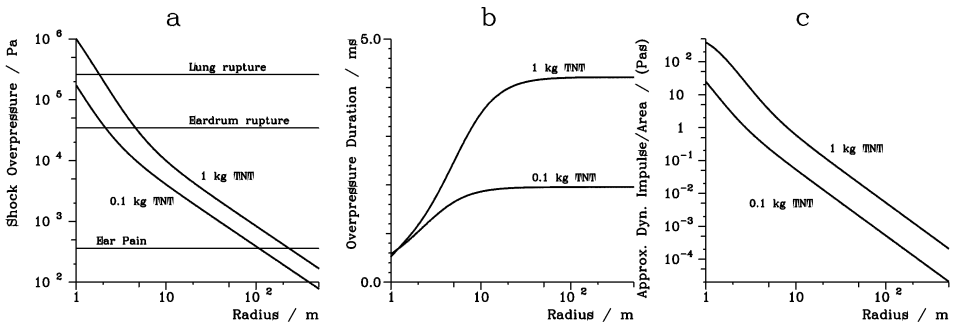

Figure A.2: Shock overpressure (a), overpressure-pulse duration (b), and approximate dynamic-pressure-caused impulse per area for unity drag coefficient (c), versus distance *r* for conventional explosions of 0.1 and 1 kg TNT at sea level in free air. The strong-shock regime with r^{-3} pressure decrease holds to about 2 and 5 m, respectively. For an explosion at hard ground the energy has to be multiplied by 2 or the distances by $2^{1/3}$=1.26. In (a), several damage thresholds are shown. Lung damage will occur below 0.8 m or 1.8 m, eardrum rupture is expected below 2 and 5 m, and some people will feel ear pain if closer than 100 m or 200 m, respectively. For distances above 1 m, the overpressure-pulse durations (b) are on the order of milliseconds. The drag-exerted impulse per area transferred to a small object can be gained from the approximate curves in (c) by multiplication with the drag coefficient.

For the present application the question is whether considerable shock energy can be focused into a narrow cone, avoiding distribution over a full sphere. Whereas shock overpressure would decrease in proportion to 1/*r* as long as the beam size would remain constant, the usual r^{-3} decrease would take over as soon as the size would increase. How far considerably stronger overpressure than for a spherical explosion would be possible needs a detailed study. However, it seems difficult to conceive of a shock wave from a 1-m source which is still bounded at, say, 50 m.

Appendix 2: Analysis of Specific Allegations with Respect to Acoustic Weapons[129]

The following sections deal with a few allegations made mostly in journalistic articles, first concerning weapons principles, then with respect to effects on humans.

Allegations Regarding Weapons Principles

Infrasound Beam from a Directed Source?

Several journalistic articles speak of an "infrasound beam" (see table 1). It is clear from the beginning (see equation (A-6)) that for long wavelengths a large emitting area will be needed to achieve substantial intensity at some distance.[130] In order to do a conservative estimate I assume a transmitter diameter of 3 m which is already fairly cumbersome, and the shortest wavelength compatible with the "infrasound" notion, namely λ =17.2 m for a frequency of ν =20 Hz at 340 m/s sound speed. For the acoustic power I take P=10 kW which might, e.g., stem from a combustion engine of 30-60 kW. The rms pressure at the source is then 0.77 kPa (level 152 dB). Because the wavelength is much larger than the emitter, the far-field intensity is the same in all directions; there can be no beam. Instead there is spherical expansion (as has been observed with the somewhat smaller MOAS device mentioned in the section on low-frequency sources).

Because of the large source and low frequency, no shock will form, and normal linear propagation with $1/r$ decrease of amplitude with radius will take place everywhere. At a notional distance of r=50 m the pressure will be 3.2 Pa (level 104 dB), several orders of magnitude below any appreciable effect of infrasound. Of course, should the sound wave, before leaving the emitting area, have passed through a much narrower duct with higher intensity, shock may have formed there, reducing the intensity outside even further.

Next, let us test the low-audio frequency of 100 Hz, the upper limit of where stronger non-auditory effects had been observed at about 150 dB level, and let us assume the same large emitter size of 3 m. In forward direction there is still spherical propagation without shock. The pressure at 50 m distance will be 16 Pa (level 118 dB), which is very loud but clearly below the pain threshold. Inner-organ effects as observed at about 150 dB will occur only immediately in front of the source. Aural pain and damage from short-term exposure is expected – in case of unprotected hearing – for distances up to a few meters.

At higher frequencies shorter wavelengths facilitate focused propagation. However, as a beam forms and becomes narrower, non-linear absorption becomes stronger in parallel. Whereas very high levels with drastic effects, e.g., on hearing or vestibular system, are possible at close distance, reaching the pain threshold at 50 m distance or beyond will be practically impossible.

Infrasound from Non-Linear Superposition of Two Directed Ultrasound Beams

One of the alleged early acoustic weapons (the "squawk box" mentioned in the introduction) was said to utilize two near-ultrasound waves which would combine in the ear, producing an intolerable infrasound difference frequency (together with the ultrasound sum frequency).[131] In a short general analysis of acoustic weapons, the requirement of non-linearity for such production was mentioned explicitly. Here, the low-frequency component of, e.g., 7 Hz produced from 40.000 and 40.007 kHz was said to disturb the vestibular organ.[132] In neither case, however, was a quantitative estimate of the conversion efficiency made.

To analyze this allegation, one needs first to recall that in controlled experiments, infrasound of levels above 140 dB did not affect the vestibular system. Non-linear production of difference-frequency signals can occur either during propagation in the air or within the ear.[133]

First to conversion in the air: as discussed with equation (A-7), for plane waves the sound pressure of the difference-frequency wave is smaller than the starting pressure of the original wave(s) by a factor of the ratio of the difference and the original frequency. Conservatively taking a high infrasonic frequency of 20 Hz and a low ultrasonic one of 16 kHz, this ratio is 1/800: the infrasound pressure will be smaller by a factor of 800 or more than the ultrasound pressure emitted at the source, i.e., the level will be lower by 58 dB or more. With 1 m emitter size the plane-wave case is approximately fulfilled.

If one conservatively assumes an infrasound level required for vestibular effects of 140 dB (200 Pa rms pressure), then the ultrasound level at the source should be about 200 dB (200 kPa = twice atmospheric pressure, already in the strong-shock realm, a factor of 100 or 40 dB above the strongest ultrasound sources available). Such pressure would correspond to an intensity of 100 MW/m^2, which – integrated over the transmitter area of 0.79 m^2 – would mean a total acoustic power of 79 MW. For infrasound effects this would probably have to be maintained over a few seconds. Such a power level seems extremely difficult to achieve, even if direct conversion from 16,000 gasoline-air explosions per second in front of a reflector were used. Reducing the power by a smaller emitter size would not help, because then the beam width would begin to grow at a shorter distance, reducing the intensity and thus the non-linear-conversion efficiency. Quantitative analysis of this hypothetical fast sequence of strong shocks would need a separate study. In reality, an intensity on the order of 1 MW/m^2 at the source may be possible eventually (180 dB, bordering on weak shock where equation (A-7) holds, see the section on potential weapon sources), this would – due to the frequency ratio – be converted to a maximum level of 120 dB, which is harmless in the infrasound region.

Thus, it seems highly improbable that non-linear difference-frequency production in the air from ultrasound to infrasound can achieve levels at which marked effects on the ear or the vestibular organ occur.

Second, conversion can take place by non-linear processes in the ear. Absent publications on difference-frequency infrasound production from high-level ultrasound in the ear, I do a simple estimate using plausible or conservative assumptions. The first is that as the sound frequency increases from the one of highest sensitivity, about 2 kHz for humans, towards the high hearing limit, the eardrum motion and consequent transfer to the inner ear decreases, mainly because of the inertia of the masses involved. For the cat, a decrease by a factor of 20 between 1 and 10 kHz has been observed;[134] conservatively, I take this value for 16 kHz and higher. Second, I use a conservatively simplified non-linear relationship between static pressure and the angle of the umbo (the eardrum centre where the malleus is connected). Again assuming vestibular effects from infrasound of 140 dB level, one arrives at a required ultrasound level of 180 dB (19 kPa) or more.

This is about a factor of 10 or 20 dB above the capabilities of the strongest periodic ultrasound sources available. Let us nevertheless assume that such levels could be produced. With standard assumptions, a 16-kHz wave starting with such level will become shocked already at 1.4 cm, after which strong absorption would start until the third, amplitude-invariant stage starts in 39 m with a level of 60 dB. Thus, the required level would be limited to the immediate vicinity of the hypothetical source. Here, however, direct damage to the ear by overload beyond the pain threshold is probable, and would represent the more drastic effect, together with heating even on bare skin (see the subsection on ultrasound).

Taking into account the conservative assumptions made, it seems therefore that neither of the non-linear mechanisms producing the difference (or modulation) frequency, in the air or in the ear, can generate anything close to inner-ear infrasound levels at which vestibular effects, or aural pain, would occur, except in the immediate vicinity of the source.

Producing an audible sound by non-linear processes in the air or in the ear where two inaudible (ultrasound) beams from separate sources intersect ("deference tone," see table 1) seems possible, on the other hand, since levels of a few tens of dB are sufficient for hearing.

Diffractionless Acoustic "Bullets"

For U.S. as well as Russian acoustic-weapon development, journalistic articles have reported non-diffracting acoustic "bullets," with, however, somewhat contradicting properties – in some reports they work at high, in others at low frequencies. For the U.S., antennas of 1-2 m size have been mentioned; in Russia, the bullets were said to be basketball-sized, with frequency of 10 Hz, and to be selectable from non-lethal to lethal over hundreds of meters (see table 1).

It is not clear what might be behind these allegations. As shown in appendix 1, diffraction does occur with all three acoustic wave types – linear, weak – and strong-shock waves. Especially with low frequencies, diffraction provides for omnidirectional propagation, as demonstrated above. The "10 Hz" statement seems to imply a wavelength of 34 m, which does of course not fit at all to a "basketball-size" wave packet. But also with higher frequencies and even in case of shock, diffraction provides for eventual beam spreading, so that essentially constant-size propagation of a strong disturbance over "hundreds of meters" seems impossible with acoustic waves from sources of the order of 1 m. This holds at least as long as the signals produced at the different parts of the source are essentially similar and periodic.

There is a principal possibility of emitting different pulsed waveforms which vary in a controlled manner across the source area in such a way that their superposition produces a pulse which remains localized in a narrow beam for a substantially larger distance than with uniform excitation from the same source area. The beam width can be smaller than the source from the beginning, down to the order of a wavelength. However, if the source has finite size, as of course required for a real device, a far field with $1/r$ decrease of amplitude will occur eventually. Such waves have been called "diffraction-free" beams, acoustic (or electromagnetic) "missiles" or "bullets," acoustic (or electromagnetic) "directed-energy pulse trains." The conditions for this effect are: transient source signals of definite (space-variant) wave shape and wide bandwidth (i.e., substantial high-frequency content), and linear propagation. With respect to acoustics, first ultrasound experiments over tens of centimeters in water have demonstrated at least some increase of the on-axis intensity over the one from uniform continuous-wave excitation of the source array.[135] However, different from electromagnetics, in acoustics there are two counteracting effects. The first one is linear absorption which increases with the square of the frequency and thus successively reduces the high frequencies as the pulse propagates. Second, for strong sound non-linear propagation leads to shock formation which occurs the earlier, the higher the amplitude and the frequency. As mentioned in appendix 1, in the shock front unusual dissipative losses occur, leading to $1/r$ decrease for a beam of constant width. Unless a detailed theoretical study or experiments prove otherwise, a skeptical attitude seems advisable towards propagation of acoustic high-power pulses essentially without beam widening over distances much larger than possible with diffraction of uniform signals. It may turn out that, even though small-signal "pencil beams" prove feasible, at higher amplitude non-linear absorption destroys the effect.

Alternatively, one might think of a soliton, i.e., a one-pulse wave propagating in a non-linear medium in such a way that its amplitude and shape do not change. This requires that the higher speed of higher excitation caused by the non-linearity (see appendix 1) is counteracted by either dispersion or dissipation, and essentially one-dimensional propagation in a channel or tube, or as a plane wave of (essentially) infinite size.[136] In free air, however, dispersion at the frequencies of interest is negligible and dissipation is too low, as the process of shock formation demonstrates. Even in a soliton-carrying medium, in three dimensions the beam expands at distances large versus the source size, resulting in reduced amplitude.[137]

There is a further possibility, namely a vortex ring which – because of its rotational character – is not described by the normal wave equations. A vortex ring – the smoke ring is an example – is usually produced by ejecting a pulse of fluid through an orifice. At its margin, rotation is produced, and surrounding fluid is entrained, after which the rotating ring – by viscous interaction with the surrounding medium – moves as a stable entity through the latter. The fluid in the torus stays the same, thus a vortex ring can transport something, as demonstrated with the smoke particles in a smoke ring. During vortex-ring travel, viscous drag entrains more external fluid and produces a wake, thus the ring loses impulse, becoming larger and slower. It has to be noted that diffraction does not apply here, and that the size increase with distance is relatively slow. Finally, the ring breaks up into general turbulence.[138] Assessing the production, propagation, and effects of vortex rings could not be done here for time and space reasons.[139] If the purpose of the ring were not to exert pressure, but only to transport some material (hot gas, irritants, or the like), the rotation speed would be less important - but in this case the qualification as "acoustic" weapon, already somewhat questionable for vortex rings proper, would no longer apply, of course. Vortex rings are another area where an in-depth study is required.[140]

It may also be that journalists or observers misunderstood something. E.g., a focused beam of invisible laser light may have produced a plasma in front of a target emitting a shock wave (see below) – the propagation to the focus would of course not count as "acoustic." A misunderstanding is also suggested by the discrepancy concerning low or high frequency or by equating "non-diffracting" with "non-penetrating" (see table 1).

Plasma Created in Front of Target, Impact as by Blunt Object

In the defence press, the small arms program liaison of the U.S. Joint Services Small Arms Program was quoted as saying that an acoustic "bullet" would incapacitate by creating a "plasma in front of the target, which creates an impact wave that is just like a blunt object. ... It causes blunt object trauma, like being hit by a baseball. Traditional bullets cause ripping, tearing. This is something different because the plasma causes the impact."[141]

Plasma creation would require overpressures of many megapascals, as they occur in the immediate vicinity of an exploding charge (and where indeed due to the temperature of several 1000 K the air does not only emit visible light, but is partially ionized).[142]

Accepting the "blunt-object" notion, the size of the shock wave would be at least comparable to the human-body size. This would mean that ears and lungs would be affected as well, with damage thresholds far below 1 MPa. Thus, shock-induced plasma with overpressures far above that would be certainly fatal. A second problem concerns the possibility of creating such strong shocks. Whereas with focused shock waves (i.e., implosions) pressures of even gigapascals can be achieved in the extremely small focus in the centre of a spherical shock tube,[143] projection to a distance much larger than the source, while avoiding spherical expansion with $1/r^3$ shock pressure decrease, seems unachievable (see above).

Thus, the possibility of plasma creation at a sizeable distance can be discarded. One can speculate whether the journalists have wrongly attributed it to acoustic weapons, whereas it was in fact meant for the pulsed chemical laser that is described one page later in the same article, again creating "a hot, high pressure plasma in the air in front of a target surface, creating a blast wave that will result in variable, but controlled effects on material and personnel."[144] In that case, the task of focusing over considerable distance would be alleviated by the short wavelength (on the order of μ m) of the laser light, and high momentary power would be easier to achieve by using short pulses.

A similar argument holds if one asks whether "blunt-object trauma" could be produced by shock waves proper at some distance. An initially bounded wave would soon become larger than the human body and would fast diffract around it, creating about the same overpressure everywhere and exerting mainly compressive forces, which can be tolerated by tissue except at air-filled cavities. Only the drag of the moving air behind the shock front would exert a net force. For a conventional explosion a shock overpressure of about 100 kPa would be required, as it occurs with 1 kg TNT spherically exploding at only about 3 m distance.[145] At such pressure an incidence of eardrum rupture above 50% is already expected which would of course be the more dramatic injury.

Thus, blunt-object trauma is only probable very close to the shock-wave source and/or where a shock-wave beam has dimensions smaller than the human body. Also here the same mix-up with the laser-generated plasma has probably occurred, and it was in fact mentioned in the same context.

The case of a vortex ring – acting only on parts of the body – needs a separate analysis, see above.

Localized Earthquakes Produced by Infrasound

An overview on non-lethal weapons has stated that acoustic weapons could affect buildings not only by shattering windows, but even by "localized earthquakes" (without giving an explicit source).[146] One might define an earthquake by a soil motion sufficient to endanger buildings, which occurs at a soil speed markedly above 10 mm/s.[147] Taking this as a conservative limit and using a maximum acoustic-seismic transfer factor of 10^{-5} m/(Pas),[148] a low-frequency sound pressure of 1 kPa (level 154 dB) is required to achieve that soil speed. As demonstrated above, such levels are possible only in the immediate vicinity of a low-frequency source, but cannot be maintained over tens of meters. Thus, if vibration levels damaging buildings are to be produced at all, they will probably not be transferred by vibration of the earth around them, but rather produced by resonances of or within the buildings, most likely within certain large rooms, directly excited by low-frequency sound energy. This could indeed produce "earthquake-like effects" inside, from rattling of tableware to breakage of windows, cracks in plaster, and in extreme situations even to collapse of brittle walls, but this would need very good coupling from the source (see also the section on protection). A misunderstanding of the phrase "earthquake-like" may be the basis of the allegation.

In a similar way, the alleged "disintegration of concrete" by infrasound,[149] which sounds as if it would occur on simple impinging and as such is incredible due to the large impedance mismatch, is only conceivable if a suitable building resonance could be exploited with good coupling from the source.[150] The same would hold for embrittlement or fatigue of metals, delamination of composite materials etc.[151]

Allegations Regarding Effects on Persons

There are a few allegations concerning high-power sound effects on humans which make a strong impression when being read, but are difficult to confirm from the scientific literature. This concerns mainly vomiting and uncontrolled defecation.[152]

Whereas vertigo or nausea in the vicinity of strong sound sources has been reported in scientific articles - often characterized as slight or transitory - actual vomiting was not reported with high audio frequencies nor with ultrasound (here dizziness seems rather to have been caused by audio contributions).[153] In close vicinity to jet engines, in a systematic study unsteadiness and imbalance were observed, but nausea occurred only in some employees sometimes after an exposure, and there was no vomiting. These authors mentioned "American reports" where one source had stated that at 13 kHz and 1 W power irritability and headache would be followed by nausea and even vomiting; however, no source for this was given.[154] Given that in other experiments people were exposed to 9.2, 10, 12, 15, and 17 kHz at levels of 140 to 156 dB for 5 minutes without any mentioning of even nausea,[155] without more information this single allegation of vomiting does not seem to deserve much weight. As to intense low-frequency sound, in the most extreme experiments carried out, mild nausea and giddiness were reported at 50 to 100 Hz with about 150 dB - but again vomiting did not occur.[156] With animals tested at low frequencies with up to 172 dB, vomiting was not mentioned at all.[157]

Evidence for bowel spasms and uncontrolled defecation is even scarcer. Among all the literature surveyed for this article, the only hint found was one on "digestive troubles" observed during experiments with a strong 16-Hz siren. These were, however, not specified at all, and the explanation immediately following talked of objects vibrating in clothing pockets.[158] In the low-frequency exposures up to 150 dB no bowel spasms were observed.[159] The same holds for low-frequency animal experiments.[160] Here it is noteworthy that also in reviewing vibration experiments no mention was made of bowel spasms or uncontrolled defecation.[161]

A third effect for which there seems to be no reliable source concerns resonances at very low frequencies of, e.g., the heart that might lead to death, as has been alleged - without further reference - in an early book.[162] Reference to the extreme 150-dB exposures at 50-100 Hz shows that the subjects suffered from several kinds of problems in the chest, but the heart - monitored by EKG - was not mentioned as troublesome.[163] Similarly, there are no indications for the alleged low-frequency-produced internal hemorrhages.[164]

Thus, it seems that these alleged effects are more based on hearsay than on scientific evidence. It cannot be excluded that at higher sound levels in specific frequency ranges, vomiting, uncontrolled defecation, or heart problems will occur, but the evidence for them is scant at best, and achieving such sound levels at some distance is extremely difficult anyway.

NOTES AND REFERENCES

1. A more detailed version of this article with more references and full appendices appears simultaneously: J. Altmann, *Acoustic Weapons - A Prospective Assessment. Sources, Propagation, and Effects of Strong Sound* (Ithaca NY: Peace Studies Program, Cornell University 1999).

2. Most of the information on non-lethal weapons comes from journalistic articles in the defence or general press. The following overview articles and books discuss various problems of non-lethal weapons and provide many references: R. Span, J. Altmann, G. Hornig, T. Krallmann, M. Rosario Vega Laso, J. Wüster, "'Non-lethal' Weapons - Fantasy or Prospect of More Humane Use of Force?" (in German), Dossier Nr. 17, Wissenschaft und Frieden (June 1994); R. Kokoski, "Non-lethal weapons: a case study of new technology developments," in: *SIPRI Yearbook 1994: World Armaments and Disarmament* (Stockholm/Oxford: SIPRI/Oxford University Press, 1994): 367-386; S. Aftergood, "The Soft-Kill Fallacy," *Bulletin of the Atomic Scientists* (Sept./Oct. 1994): 40-45; A. Roland-Price, "Non-Lethal Weapons: A Synopsis," in: U.S. Congress, Office of Technology Assessment, "Improving the Prospects for Future International Peace Operations - Workshop Proceedings," OTA-BP-ISS-167 (Washington DC: U.S. Government Printing Office, Sept. 1995); J. Altmann, "'Non-Lethal' Weapons," in: J. Rotblat (ed.), *Security, Cooperation and Disarmament: The Unfinished Agenda for the 1990s* (Singapore etc.: World Scientific, 1998); M. Dando, *A New Form of Warfare - The Rise of Non-Lethal Weapons* (London/Washington: Brassey's, 1996); N. Lewer, S. Schofield, *Non-Lethal Weapons: A Fatal Attraction? Military Strategies and Technologies for 21st-Century Conflict* (London/New Jersey: Zed Books, 1997). There are not many systematic and comprehensive publications by proponents of non-lethal weapons. The following references give some examples of proponents' writing: "Nonlethality: A Global Strategy Whitepaper" (Washington DC: U.S. Global Strategy Council, 1992); J. B. Alexander, "Nonlethal Weapons and Limited Force Options," presented to Council of Foreign Relations, New York, 27 Oct. 1993; Milt Finger, "Technologies to Support Peacekeeping Operations," in: U.S. Congress, Office of Technology Assessment (ibid.); G. Yonas, "The Role of Technology in Peace Operations"; in: U.S. Congress, Office of Technology Assessment (ibid.); C. Morris, J. Morris, T. Baines, "Weapons of Mass Protection - Nonlethality, Information Warfare, and Airpower in the Age of Chaos," *Airpower Journal* 9, no. 1 (Spring 1995): 15-29; D. A. Morehouse, *Nonlethal Weapons - War Without Death* (Westport CT/London: Praeger, 1996). For a balanced view from inside the U.S. military, see: J. W. Cook III, D. P. Fiely, M. T. McGowan, "Nonlethal Weapons - Technologies, Legalities, and Potential Policies," *Airpower Journal* 9, Special Issue (1995): 77-91. NLW developments for law-enforcement purposes are presented in considerable detail e.g. in: J. Alexander, D. D. Spencer, S. Schmit, B. J. Steele (eds.), "Security Systems and Nonlethal Technologies for Law Enforcement," *Proc. SPIE* 2934 (1997). All kinds of activity are described in the contributions to the conference of the National Defense Industrial Association "Non-Lethal Defense III," Johns Hopkins University, 25 and 26 Febr. 1998, http://www.dtic.mil/ndia/NLD3/index.html.

3. Morehouse (note 2).

4. E.g.: A. W. Debban, "Disabling Systems: War-Fighting Option for the Future," *Airpower Journal* 7, no. 1 (Spring 1993): 44-50; Roland-Price (note 2).

5. It seems that other Western industrialized countries rather take a wait-and-see approach, mainly doing paper studies to keep up to date, see: Altmann 1996 (note 2); reports from Russia indicate that there is considerable interest in non-lethal weapons as well, examples include directed-energy weapons and an acoustic bullet, see: Kokoski

(note 2), 373; M. T., “Russians Continue Work on Sophisticated Acoustic Weaponry,” *Defense Electronics* 26, no. 3 (March 1994): 12.

6. These considerations may have been among the motives in the recent rethinking by the U.S. of its position towards laser blinding weapons. In June 1995 the Department of Defense was on the verge of buying 50 LCMS laser blinding rifles and planned to acquire 2,500 more. But in September 1995 it changed its policy, and in December 1995 (after the wording had been changed to accommodate US and other interests) the U.S. signed the new Additional Protocol to the UN Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons Which May Be Deemed to Be Excessively Injurious or to Have Indiscriminate Effects (“Certain Weapons Convention,” “Inhumane Weapons Convention”) of 1980. See: “Blinding Laser Weapons: The Need to Ban a Cruel and Inhumane Weapon,” *Human Rights Watch Arms Project* 7, no. 1 (Sept. 1995); text of the Protocol in: “Trust and Verify,” no. 62 (London: Verification Technology Information Centre, Nov./Dec. 1995).

7. The Biological Weapons Convention of 1972 bans any hostile use of biological agents, irrespective of whether the target is a living organism or equipment; Finger (note 2) is wrong in this respect. See: Altmann 1996 (note 2); Cook et al. (note 2). However, the Chemical Weapons Convention of 1992 only prohibits toxic chemicals which can cause death, temporary incapacitation or permanent harm to humans or animals.

8. The most prominent example is the case of laser blinding weapons, use of which fortunately has been banned in 1995, see note 6.

9. See also: B. Starr, “Non-lethal weapon puzzle for US Army,” *International Defense Review* 4 (1993): 319-320.

10. Morehouse (note 2), p. 119.

11. Such assessment of new military technologies is one part of preventive arms limitations; for examples of other technologies see: J. Altmann, “Verifying Limits on Research and Development - Case Studies: Beam Weapons, Electromagnetic Guns,” in: J. Altmann, T. Stock, J.-P. Stroot (eds.), *Verification After the Cold War - Broadening the Process* (Amsterdam: VU Press, 1994).

12. Additional sources not included in the table: B. Starr, “U.S. tries to make war less lethal,” *Jane's Defence Weekly* (31 Oct. 1992): 10; A. and H. Toffler, “War and Anti-War. Survival at the Dawn of the 21st Century” (Boston etc.: Little, Brown and Co. 1993) (here: ch. 15, “War without Bloodshed?”) (quoted after the German translation: “Überleben im 21. Jahrhundert” (Stuttgart: DVA 1994)); Debban (note 4). Alexander (note 2); J. Barry, T. Morganthau, “Soon, ‘Phasers on Stun,’” *Newsweek* (7 Febr. 1994): 26-28; Kokoski (note 2); Aftergood (note 2), G. Frost, C. Shipbaugh, “GPS Targeting Methods for Non-Lethal Systems,” Reprint RAND/RP-262 (1996) (reprinted from IEEE Plans 94); Cook et al. (note 2); Morehouse (note 2), p. 20, 119 f.; Dando (note 2), p. 11 ff; SARA report of 10 Febr. 1995 (revised 13 Febr. 1996) and other references as reported by: W. Arkin, “Acoustic Anti-personnel Weapons: An Inhumane Future?,” *Medicine, Conflict and Survival* 14, no. 4 (1997): 314-326.

13. M. Lumsden, *Anti-personnel Weapons* (Stockholm/London: SIPRI/Taylor&Francis 1978): 203-205.

14. “Army tests new riot weapon,” *New Scientist* (20 September 1973): 684; C. Ackroyd, K. Margolis, J. Rosenhead, T. Shallice, *The Technology of Political Control* (2nd ed.) (London: Pluto, 1980): 224-225. See also: R. Rodwell, “‘Squawk box’ technology,” *New Scientist* (20 September 1973): 667.

15. "Non-lethality ..." (note 2).

16. V. Kiernan, "War over weapons that can't kill," *New Scientist* (11. Dec. 1993): 14-16.

17. Lewer/Schofield (note 2), 8 ff.

18. P. R. Evancoe, "Non-Lethal Technologies Enhance Warrior's Punch," *National Defense* (Dec. 1993): 26-29.

19. M. Tapscott, K. Atwal, "New Weapons That Win Without Killing On DOD's Horizon," *Defense Electronics* (Febr. 1993): 41-46.

20. Starr (note 9).

21. "Army Prepares for Non-Lethal Combat," *Aviation Week & Space Technology* (24 May 1993): 62.

22. M. T. (note 5).

23. N. Broner, "The Effects of Low Frequency Noise on People - A Review," *Journal of Sound and Vibration* 58, no. 4 (1993): 483-500; O. Backteman, J. Köhler, L. Sjöberg, "Infrasound - Tutorial and Review: Part 4," *Journal of Low Frequency Noise and Vibration* 3, no. 2 (1984): 96-113. Broner cites: J. F. J. Johnston, *Infrasound - a Short Survey* (Royal Military College of Science, England, 1971). Backteman et al. have copied the respective paragraph from Broner virtually identically, leaving out two sentences and two references, without giving the source.

24. R. Applegate, *Riot Control - Material and Techniques* (Harrisburg PA: Stackpole, 1969): 273.

25. Applegate (note 24), 271-273. In 1973 the British government bought 13 such systems for the use in Northern Ireland, but they seem to not have been used there. See: Ackroyd et al. (note 14), 223-224.

26. Johnston (note 23), quoted in Broner (note 23). For the use of white noise on prisoners see also: Lumsden (note 13) and references given there.

27. "Army tests ..." (note 14); Ackroyd et al. (note 14), 224-225. See also: Rodwell (note 14).

28. In a subsequent press conference, the British Army instead presented the 350-W amplifier/speaker system (see note 24) of which 13 copies had been bought, but "forgot" to invite the *New Scientist* reporter who had written the "squawk box" article, see: R. Rodwell, "How dangerous is the Army's squawk box?," *New Scientist* (27 September 1973): 730.

29. Ackroyd et al. (note 14), 224-225.

30. M. Bryan, W. Tempest, "Does infrasound make drivers drunk?," *New Scientist* (16 March 1972): 584-586; R. Brown, "What levels of infrasound are safe?," *New Scientist* (8 Nov. 1973): 414-415; H. E. von Gierke, D. E. Parker, "Infrasound," ch. 14 in: W. D. Keidel, W. D. Neff (eds.), "Auditory System - Clinical and Special Topics," *Handbook of Sensory Physiology*, vol. V/3 (Berlin etc.: Springer, 1976): section VII.

31. Starr (note 9).

32. Tapscott/Atwal (note 19). See also: http://www.pica.army.mil/pica/products/tbiwc.html.

33. Starr (note 9). See also: http://www.sara.com/documents/future.htm. Similar infor-

mation is provided by Tapscott/Atwal (note 19); they state that Los Alamos National Laboratory (LANL) is involved in acoustic beams, too, whereas Starr mentions LANL only for optical munitions and high-power microwave projectiles. A LANL brochure on non-lethal weapons contains the latter two, but not acoustic weapons: "Special Technologies for National Security" (Los Alamos NM: Los Alamos National Laboratory, April 1993).

34. M. T. (note 5).

35. SARA Report, 10 February 1995 (revised 13 February 1996) and other references as reported by Arkin (note 12).

36. With infrasound, no pain or nausea was observed even up to 172 dB, see section 2.2 below. With audible sound, there was no physical trauma and damage to tissues up to above 150 dB, see 2.3.

37. Tens of meters are more realistic, see appendix 2.

38. Note that the infrasound research seems to have been refocused recently, see: J. Hecht, "Not a sound idea," *New Scientist*, 20 March 1999, 17.

39. E.g., vertigo, nausea, and vomiting are ascribed to infrasound at 130 dB (correct: none to 172 dB, see section 2.2.3.2 below), and a blast wave would lead to eardrum rupture at 130 dB (correct: above 185 dB, see 2.5): Kap. 3.8, see "Konzeptbeschreibungen akustischer Wirkmittel" in J. Müller et al., *Nichtletale Waffen, Abschlußbericht*, Band II, Dasa-VA-0040-95=OTN-035020, Daimler-Benz Aerospace, 30. 4. 1995, 307-333.

40. A. Dähn, "Angriff auf das Trommelfell"; *Berliner Zeitung*, 24 March 1999; K.-D. Thiel, "Non-Lethal Weapons Activities at ICT," in *Non-Lethal Defense III* (note 2), file ict.pdf.

41. Lumsden (note 13); L. Liszka, "Sonic Beam Devices - Principles" in *Expert Meeting on Certain Weapon Systems and on Implementation Mechanisms in International Law*, Geneva, 30 May - 1 June 1994, Report (Geneva: International Committee of the Red Cross, July 1994), 89-91.

42. Arkin (note 12).

43. My subject is only sound in air. Potential underwater applications, e.g., against divers or animals, need a separate study.

44. For transient pressure variations the level is often defined using the maximum pressure occurring, not the rms value.

45. For a discussion of blast weapons, see Lumsden (note 13) chap. 6.

46. SARA (note 12).

47. For space reasons, in the section on effects several details and references have been left out. For the complete information see Altmann (note 1).

48. F. G. Hirsch, "Effects of Overpressure on the Ear - A Review," *Annals of the New York Academy of Sciences* 152(Art. 1) (1968): 147-162; W. D. Keidel, W. D. Neff (eds.), "Auditory System - Anatomy, Physiology (Ear)," in *Handbook of Sensory Physiology*, vol. V/1 (Berlin etc.: Springer, 1974); Karl D. Kryter, *The Effects of Noise on Man* (New York etc.: Academic 1970; second edition 1985), ch. 1; v. Gierke/Parker (note 30); W. Melnick, "Hearing Loss from Noise Exposure," in C. M. Harris (ed.), *Handbook of Acoustical Measurements and Noise Control* (New York etc.: McGraw-Hill, 1991) ch. 18; W. D. Ward, "Noise-Induced Hearing Damage," in M. M. Paparella et al. (eds.), *Oto-*

laryngology vol. II (3rd edition Philadelphia etc.: Saunders 1991) ch. 45; B. Berglund, P. Hassmén, "Sources and effects of low-frequency noise," *Journal of the Acoustical Society of America* 99(5) (May 1996): 2985-3002.

49. H.-G. Boenninghaus mit T. Lenarz, Hals-Nasen-Ohrenheilkunde für Studierende der Medizin, 10. Aufl., Berlin etc.: Springer, 1996.

50. Note that PTS can accumulate over a long time even if recovery from TTS occurs daily.

51. Note that sometimes also long-term injury comes under this heading, and damage from short exposure is called acute acoustic trauma.

52. Loudness is measured by comparing subjective perception of tones at other frequencies with the one at 1 kHz. At 1 kHz, loudness levels in phone are defined to be equal to the respective sound pressure levels in decibels.

53. N. S. Yeowart, M. J. Evans, "Thresholds of audibility for very low-frequency pure tones," *Journal of the Acoustical Society of America* 55, no. 4 (April 1974): 814-818; A. M. Small, Jr., R. S. Gales, "Hearing Characteristics," in Harris (note 48), chap. 17. H. Møller, J. Andresen, "Loudness of Pure Tones at Low and Infrasonic Frequencies," *Journal of Low Frequency Noise and Vibration* 3, no. 2 (1984): 78-87; Berglund/Hassmén (note 48); Melnick (note 48); H. E. von Gierke, C. W. Nixon, "Effects of Intense Infrasound on Man," in W. Tempest (ed.), *Infrasound and Low Frequency Vibration* (London etc.: Academic, 1976), ch. 6, 134; v. Gierke/Parker (note 30), 604.

54. E.g. see the sensational article "The Low-Pitched Killer - Can sounds of silence be driving us silly" (*Melbourne Sunday Press*, 7 Sept. 1975), reproduced in Broner (note 23); see also note 30. Within science, it is interesting what Lumsden writes about a meeting of the British Association on the Advancement of Science where the "Director of the [British] Noise Abatement Society reported that at a research centre at Marseille, France, an infrasound generator had been built which generated waves at 7 Hz. He said that when the machine was tested, people in range were sick for hours. The machine could cause dizziness, nervous fatigue and 'seasickness' and even death up to 8 km away (*Associated Press*, Leicester, England, 9 September 1972)." Lumsden (note 13), 204. This obviously refers to Gavreau's work done at Marseille, see V. Gavreau, R. Condat, H. Saul, "Infra-Sons: Générateurs, Détecteurs, Propriétés physiques, Effets biologiques," *Acustica* 17, no. 1 (1966): 1-10; V. Gavreau, "Infrasound," *Science Journal* 4, no. 1 (Jan. 1968): 33-37. Note that today scientists at the same institute have some doubts about the conclusions drawn by Gavreau on the effects of infrasounds, because his experiments and observations have not been replicated and confirmed under accurate experimental conditions. G. Canevet, Laboratoire de Mécanique et d'Acoustique CNRS, Marseille, personal communication.

55. Thus, in the determination of the capabilities of hearing much care is needed to keep nonlinearities in sound production very low lest the externally generated harmonics at higher and better audible frequencies lead to erroneously high values.

56. With dogs and cats, less pathological damage was observed. On the other hand, thirty seconds of exposure to 172 dB infrasound did not even produce reddening in a human eardrum.

57. There is one documented case where at 6.5 kHz, a small rupture and blood in the external ear canal was observed with one experimenter after 5 minutes exposition to about 158 dB (1.6 kPa): H. Davis, H. O. Parrack, D. H. Eldredge, "Hazards of Intense Sound and Ultrasound," *Annals of Otology, Rhinology, Laryngology* 58 (1949): 732-738.

58. C. Mohr, J. N. Cole, E. Guild, H. E. von Gierke, “Effects of Low Frequency and Infrasonic Noise on Man,” *Aerospace Medicine* 36, no. 9 (1965): 817-824. Concerning the stronger effects at low audio frequencies reported by Mohr et al., note that there are doubts at the same laboratory today whether these were due to oil droplets in the compressor air and not to the sound. The experiments are to be repeated in 1999. R. McKinley, Aural Displays and Bioacoustics Branch, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, U.S., personal communication.

59. Humans can stand quite high accelerations. In experiments with frequencies between 1 and 25 Hz, the subjective tolerance was reached at a few times the normal gravity acceleration ($g=9.8$ m/s^2); subjects suffered, inter alia, from dyspnoea, chest and periumbilical pain, and sometimes gastrointestinal bleeding. However, no lasting effects were observed.

60. If the sound pressure would affect only a part of the body surface, sideward movement and shear waves in the tissue would result with much greater energy deposition.

61. Note that for near-daily exposition of humans over 10 years to short tones, much lower damage-limiting levels of 130 to 115 dB were estimated. For the maximum instantaneous sound pressure occurring in an isolated event during a working day, 200 Pa (140 dB) has been given.

62. See note 57.

63. The authors described a “most unpleasant and disturbing sensation of general instability and weakness”; nausea, true dizziness, visual disturbances, or nystagmus were not observed. Ear protection stopped the effect. See E. D. D. Dickson, D. L. Chadwick, “Observations on Disturbances of Equilibrium and Other Symptoms Induced by Jet Engine Noise,” *Journal of Laryngology and Otology* 65 (1951): 154-165. This seems to be the only article which reasonably reliably and completely describes the symptoms and circumstances of equilibrium disturbances close to jet engines. Later studies of ground or flight-deck personnel do not mention equilibrium problems, even though personnel was exposed to levels up to above 140 dB, often without ear protection. Dickson/Chadwick of 1951 was cited to the 80s.

64. Among the about 1800+450 articles produced by a Medline search for (injury or impairment) and (sound or noise or ultrasound), or (acoustic trauma), respectively, from 1966 to 1998, I have only found four (potentially) describing injury due to tonal or broad- or narrow-band noise of level about or above 140 dB. On the other hand, there are many articles about damage due to impulse noise of levels of 150 dB and more, see section 2.5 in Altmann (note 1).

65. Rats and mice were killed by overheating within minutes at audio and ultrasound frequencies.

66. Pulses of fast rise time and duration above 3 ms, produced at repetition rates of 6-30/min to no more than 100 at one exposure, would not cause excessive hearing loss in 75% of the exposed people.

67. Knocking a person down, which occurs with nuclear blasts of 0.5 to 1 s duration at 7-10 kPa overpressure (171-174 dB), see G. F. Kinney, K. J. Graham, *Explosive Shocks in Air* (New York etc.: Springer, 1985), table XV, is not relevant with shock waves from conventional explosions. Durations of conventional-explosion shock waves are only a few ms and thus the impulse transferred, i.e., the time integral over the drag force, is correspondingly smaller for equal peak overpressure. Only at very close distance (below a few meters) would the impulse suffice, but here other damage (to the ear-

drum, the lungs) would be more relevant, see appendix 1.

68. For this and the following examples see also: D. L. Johnson, "The Effects of High Level Infrasound," in: H. Møller, P. Rubak (eds.), *Conference on Low Frequency Noise and Hearing,* 7-9 May 1980, Aalborg, Denmark.

69. See Altmann (note 1), appendix A.4.

70. N. S. Yeowart, M. E. Bryan, W. Tempest, "The Monaural M.A.P. Threshold of Hearing at Frequencies from 1.5 to 100 c/s," *Journal of Sound and Vibration* 6 (1967): 335-342; see also: M. J. Evans, "Physiological and Psychological Effects of Infrasound at Moderate Intensities," in *Tempest* (note 53) chap. 5.

71. N. S. Yeowart, M. E. Bryan, W. Tempest, "Low-frequency Noise Thresholds," *Journal of Sound and Vibration* 9 (1969): 447-453; see also: v. Gierke/Nixon (note 53).

72. D. L. Johnson, "Various Aspects of Infrasound," in L. Pimonow (ed.), *Colloque international sur les infra-sons* (Paris: Centre National de Recherche Scientifique, 1974): 129-153, cited after: v. Gierke/Parker (note 30). Fig. 2 in v. Gierke/Nixon (note 53) shows "piston stroke 12 cm d.a."

73. Assuming a large baffle, from equation (A-10) in: Altmann (note 1).

74. For an overview over natural sources, see T. B. Gabrielson, "Infrasound" in M. J. Crocker (ed.), *Encyclopedia of Acoustics* (New York etc.: Wiley, 1997) ch. 33, and literature cited there. Note that for very slow pressure variations the Eustachian tube provides equalization of the middle-ear pressure.

75. R. D. Hill, "Thunder" in R. H. Golde (ed.), *Lightning,* vol. 1 (London etc.: Academic, 1977) chap. 11.

76. Johnson (note 68); own calculations.

77. Backteman et al. (note 23); Berglund/Hassmén (note 48).

78. Backteman et al. (note 23).

79. Johnson (note 68); v. Gierke/Nixon (note 53).

80. From own measurements of MiG-21 and Tornado fighter-bombers, see J. Altmann, R. Blumrich, "Acoustic and Seismic Signals during Aircraft Take-offs and Landings" (in German) in *Fortschritte der Akustik - DAGA 94* (Bad Honnef: DPG-GmbH. 1994): 417-420; R. Blumrich, *Sound Propagation and Seismic Signals of Aircraft used for Airport Monitoring - Investigations for Peace-keeping and Verification* (Hagen: ISL, 1998).

81. Mohr et al. (note 58); v. Gierke/Parker (note 30).

82. v. Gierke/Nixon (note 53).

83. v. Gierke/Nixon (note 53); v. Gierke/Parker (note 30).

84. H. C. Sommer, C. W. Nixon, "Primary components of simulated air bag noise and their relative effects on human hearing," Report, AMRL-TR-73-52 (Wright-Patterson Air Force Base OH: Aerospace Medical Research Laboratory 1973), cited after: v. Gierke/Parker (note 30), section V; Johnson (note 68).

85. H. G. Leventhall, "Man-made infrasound - its occurrence and some subjective effects" in Pimonow (note 72), quoted after v. Gierke/Nixon (note 53).

86. For general articles on loudspeaker arrays, see the special issue of *Journal of the Audio Engineering Society Audio/Acoustics/Applications* 38, no. 4 (April 1990).

87. With layers of extremely porous, but stiff aerogels on the membrane, impedances could match and coupling could be much improved. This possibility is also mentioned by Finger (note 2).

88. For the efficiency figures see: B. M. Starobin, "Loudspeaker Design" in Crocker (note 74) chap. 160; see also V. Salmon, "Horns," in Crocker (note 74) ch. 61, and literature cited there.

89. The 40° held for the 68 cm long exponential horns with combined diameter 71 cm; there was also a 2.1 m long extension. R. C. Jones, "A Fifty Horsepower Siren," *Journal of the Acoustical Society of America* 18, no. 2 (Oct. 1946): 371-387.

90. C. H. Allen, I. Rudnick, "A Powerful High Frequency Siren," *Journal of the Acoustical Society of America* 19, no. 5 (Sept. 1947): 857-865; C. H. Allen, H. Frings, I. Rudnick, "Some Biological Effects of Intense High Frequency Airborne Sound," *Journal of the Acoustical Society of America* 20, no. 1 (Jan. 1948): 62-65.

91. H. O. Parrack, "Ultrasound and Industrial Medicine," *Industrial Medicine and Surgery* 21, no. 4 (April 1952): 156-164.

92. J. Sabatier, "Acoustical Characterization of the Mother of All Speakers" (master's thesis, National Center for Physical Acoustics,1993); <http://w3.arl.mil/tto/ARLDTT/FoxProdata/fac50.html>.

93. Assuming that the sound pressure is approximately equal across the 2.3 m wide mouth, the area ratio to the equivalent 1-m-radius sphere emitting 20 kW results in about 4.8 kW/m^2 (157 dB). Spherical spreading with $1/r^2$ decrease of intensity can be assumed already close to the mouth. Note also that there is frequency-dependent directivity: the sound pressure decreases off the horn axis the faster, the higher the frequency (but above the frequency where the first null of (A-4) occurs the decrease is not monotonical because of sidelobes). With a slightly smaller horn of 2.1 m diameter, at 40 Hz (ka=0.8) the intensity was still essentially the same in all directions.

94. E.g., with meter-size enlarged models of police whistles or Levavasseur whistles 196 and 37 Hz have been produced at up to about 2 kW power, more would have been possible with higher air flow and larger whistles. See: Gavreau et al. 1966 (note 54); see also: Gavreau 1968 (note 54).

95. Yu. Ya. Borisov, "Acoustic Gas-Jet Generators of the Hartmann Type," in L. D. Rozenberg (ed.), *Sources of High-Intensity Ultrasound* (New York: Plenum 1969) part I; see also Parrack 1952 (note 91); H. Kuttruff, "Physik und Technik des Ultraschalls" (Stuttgart: Hirzel, 1988): 140 f.

96. J. A. Gallego-Juarez, G. Rodriguez-Corral, L. Gaete-Garreton, "An ultrasonic transducer for high power applications in gases," *Ultrasonics* 16 (November 1978): 267-271.

97. According to equation (A-14) to (A-24) in Altmann (note 1).

98. J. A. Gallego-Juarez, L. Gaete-Garreton, "Experimental Study of Nonlinearity in Free Progressive Acoustic Waves in Air at 20 kHz," 8e Symposium International sur l'acoustique non linéaire, *Journal de Physique* 41, Colloque C-8, suppl. au no. 11 (Nov. 1979): C8-336 - C8-340; the total level was estimated from the levels of the individual harmonics.

99. Altmann (note 1), appendix A.4 and fig. A.2.

100. Altmann (note 1), appendix A.4.

101. Megawatt power was mentioned by SARA (note 12).

102. Altmann (note 1), section 3.2.

103. For treatments of slightly related problems see: Y. Inoue, T. Yano, "Propagation of strongly nonlinear plane waves," *Journal of the Acoustical Society of America* 94, no. 3 pt. 1 (Sept. 1993): 1632-1642; Y. Inoue, T. Yano, "Strongly nonlinear waves and streaming in the near field of a circular piston," *Journal of the Acoustical Society of America* 99, no. 6 (June 1996): 3353-3372.

104. The DASA report discusses concepts of a 0.5 kg whistling system for hand throwing to 10-50 m (working about 30 seconds), and a 5 kg system for air-gun delivery to 300 m from a small truck (duration about 5 minutes), both producing 120 dB in 1 m at 1-10 kHz, see: Müller (note 39).

105. C. W. Nixon, E. H. Berger, "Hearing Protection Devices" ch. 21 in Harris (note 48). For individual attenuation values, including the helmet, see J. C. Webster, P. O. Thompson, H. R. Beitscher, *Journal of the Acoustical Society of America* 28, no. 4 (July 1956): 631-638.

106. G. Jansen, "Influence of High Noise Intensities on the Human Organism" (in German), Wehrmedizinische Monatsschrift no. 10 (1981): 371-379.

107. R. Moulder, "Sound-Absorptive Materials," in Harris (note 48) chap. 30

108. For a rectangular room, half of the longest resonance wavelength equals the longest dimension. Thus, e.g., for 5 m length 34 Hz is the lowest resonance frequency.

109. There is of course a considerable body of medical literature on aural injuries and their treatment, see e.g.: Paparella et al. (note 48). Therapy for sub-lethal blast damage to other organs than the ear will not be discussed here, because the ear damage will be prominent, and because the former does not come under the "acoustic" rubric.

110. Ward 1991 (note 48). See also R. Probst et al., "A Randomized, Double-blind, Placebo-controlled Study of Dextran/Pentoxifylline Medication in Acute Acoustic Trauma and Sudden Hearing Loss," Acta Otolaryngologica (Stockholm) 112, no. 3 (1992): 435-443.

111. Ward 1991 (note 48).

112. R. H. Chait, J. Casler, J. T. Zajtchuk, "Blast Injury of the Ear: Historical Perspective," *Annals of Otology, Rhinology & Laryngology* 98, no. 5 pt. 2, Suppl. 140 (May 1989): 9-12; J. D. Casler, R. H. Chait, J. T. Zajtchuk, "Treatment of Blast Injury to the Ear," *Annals of Otology, Rhinology & Laryngology* 98, no. 5 pt. 2, Suppl. 140 (May 1989): 13-16; and respective references.

113. See e.g.: A. G. Kerr, J. E. T. Byrne, "Concussive effects of bomb blasts on the ear," *Journal of Laryngology and Otology* 89, no. 2 (Febr. 1975): 131-143.

114. Papers of International Cochlear Implant, Speech and Hearing Symposium, *Annals of Otology, Rhinology & Laryngology* 104, no. 9 pt. 2, Suppl. 166/ (Sept. 1995): 1-468; for acquired deafness with potential induction by noise see J. S. Thomas, "Cochlear Implantation in the Elderly," ibid., pp. 91-93; R. K. Shepherd et al., "The Central Auditory System and Auditory Deprivation: Experience with Cochlear Implants in the Congenitally Deaf," Acta Otolaryngologica (Stockholm) Supplement 532 (1997): 28-33; M. J. A. Makhdoum, A. F. M. Snik, P. van den Broek, "Cochlear implantation: a review of the literature and the Nijmegen results," *Journal of Laryngology and Otology* 111 (Nov. 1997): 1008-1017; papers of third European Symposium

on Pediatric Cochlear Implantation, *American Journal of Otology* 18, no. 6 Suppl. (Nov. 1997): S1-S172.

115. Ward 1991 (note 48).

116. L. Doswald-Beck (ed.), "Blinding Weapons: Reports of the Meetings of Experts Convened by the International Committee of the Red Cross on Battlefield Laser Weapons, 1989-1991" (Geneva: International Committee of the Red Cross 1993): 336; "Blinding laser weapons ..." (note 6): 28 ff.

117. R. M. Coupland (ed.), "The SIrUS Project - Towards a determination of which weapons cause 'superfluous injury or unnecessary suffering'" (Geneva: International Committee of the Red Cross, 1997).

118. For details, see appendices A.1-A.4 of Altmann (note 1).

119. E.g.: E. Skudrzyk, *The Foundations of Acoustics - Basic Mathematics and Basic Acoustics* (New York/Wien: Springer, 1971); P. M. Morse, K. U. Ingard, *Theoretical Acoustics* (New York etc.: McGraw-Hill, 1968); A. D. Pierce, *Acoustics - An Introduction to Its Physical Principles and Applications* (Woodbury NY: Acoustical Society of America, 1991).

120. Without the pipe, acoustic short-circuit between the front and back of the piston would occur at low frequencies - this is the reason why loudspeakers are usually mounted in closed boxes.

121. See also: H. Levine, J. Schwinger, "On the Radiation of Sound from an Unflanged Circular Pipe," *Physical Review* 73 (1948): 383-406.

122. See e.g.: Salmon (note 88) and literature cited there.

123. Starobin (note 88).

124. See e.g.: O. V. Rudenko, S. I. Soluyan, *Theoretical Foundations of Nonlinear Acoustics* (New York/London: Consultants Bureau, 1977); G. B. Whitham, *Linear and Nonlinear Waves* (New York etc.: Wiley, 1974); M. F. Hamilton, D. T. Blackstock (eds.), *Nonlinear Acoustics* (San Diego etc.: Academic, 1998).

125. Non-linear sound propagation and the interaction with diffraction and absorption are fields of active research. Especially for pulsed sources, there is a need for more work, see the concluding remarks of: J. N. Tjøtta, S. Tjøtta, "Nonlinear Equations of Acoustics" in M. F. Hamilton, D. T. Blackstock (eds.), *Frontiers of Nonlinear Acoustics: Proceedings of 12th ISNA* (London: Elsevier, 1990): 80-97. For on-going research, see the series of International Symposia on Non-linear Acoustics.

126. See e.g.: Rudenko/Soluyan (note 124).

127. Ya. B. Zel'dovich, Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, vol. I (New York/London: Academic Press, 1966); Whitham (note 124); S. Glasstone, P. J. Dolan, "The Effects of Nuclear Weapons" (Washington DC: Government Printing Office, 1977) (ch. III); Kinney/Graham (note 67).

128. W. D. Ward, W. Selters, A. Glorig, "Exploratory Studies on Temporal Threshold Shift from Impulses," *Journal of the Acoustical Society of America* 33, no. 6 (June 1961): 781-793.

129. For details, see: Altmann (note 1), section 5. and appendices A.5-A.7.

130. The detailed analysis, including estimates from 500 Hz to 10 kHz, is given in: Altmann (note 1), appendix A.5.

131. "Army tests ..." (note 14).

132. Liszka (note 41).

133. Both cases are treated in: Altmann (note 1), appendix A.6.

134. J. J. Guinan, Jr., W. T. Peake, "Middle-Ear Characteristics of Anesthetized Cats," *Journal of the Acoustical Society of America* 41, no. 5 (1967): 1237-1261. Note that in their anesthetized animals the middle-ear muscles were relaxed so that the aural reflex reducing transmission was not working. Thus the estimate made here is even more conservative.

135. There is much more literature on electromagnetic and optical than on acoustic narrow pulsed beams, and much more theoretical work than experimental. See e.g.: R. W. Ziolkowski, "Localized transmission of electromagnetic energy," *Physical Review* A 39, no. 4 (Febr. 15, 1989): 2005-2033, and references cited therein; Gang Wang, Wen Bing Wang, "Beam characteristics of short-pulse radiation with electromagnetic missile effect," *Journal of Applied Physics* 83, no. 10 (15 May 1998): 5040-5044. Note that the "bullet" notion is even used for a pulse "shot" through a conically expanding "rifle": A. Stepanishen, "Acoustic bullets/transient Bessel beams: Near to far field transition via an impulse response approach," *Journal of the Acoustical Society of America* 103, no. 4 (April 1998): 1742-1751. For the ultrasound experiment see: R. W. Ziolkowski, D. K. Lewis, "Verification of the localized-wave transmission effect," *Journal of Applied Physics* 68, no. 12 (15 Dec. 1990): 6083-6086.

136. E.g.: E. Infeld, G. Rowlands, *Nonlinear waves, solitons and chaos* (Cambridge etc.: Cambridge University Press 1990); M. Remoissenet, "Waves Called Solitons - Concepts and Experiments," (Berlin etc.: Springer 1994).

137. For a discussion of non-amplitude-preserving collapsing or expanding "solitons" in two- or three-dimensional plasma and other media, see Infeld/Rowlands (note 136), chap. 9.

138. For vortex-ring dynamics, see: H. Lamb, *Hydrodynamics* (6th edition, Cambridge: Cambridge University Press 1932), chap. VII; P. G. Saffman, *Vortex Dynamics* (Cambridge: Cambridge University Press 1992), chap. 10; K. Shariff, A. Leonard, "Vortex Rings," *Annual Review of Fluid Mechanics* 24 (1992): 235-279; and respective references. For experiments and theory on propagation losses see: T. Maxworthy, "The structure and stability of vortex rings," *Journal of Fluid Mechanics* 51, no. 1 (1972): 15-32; T. Maxworthy, "Turbulent vortex rings," *Journal of Fluid Mechanics* 64, no. 2 (1974): 227-239; T. Maxworthy, "Some experimental studies of vortex rings," *Journal of Fluid Mechanics* 81, no. 3 (1977): 465-495.

139. For a few preliminary indications see: Altmann (note 1), section 5.1.3.

140. For some information on U.S. efforts at vortex-ring weapons, see G. Lucey, L. Jasper, "Vortex Ring Generators," in *Non-Lethal Defense III* (note 2), paper lucey.pdf; J. Dering, "High Energy Toroidal Vortex for Overlapping Civilian Law Enforcement and Military Police Operations" (ibid.), paper jd.pdf.

141. Tapscott/Atwal (note 19), p. 45.

142. Altmann (note 1), appendix A.7.

143. See e.g.: I. I. Glass, J. P. Sislian, *Nonstationary Flows and Shock Waves* (Oxford: Clarendon, 1994), chap. 12.

144. Tapscott/Atwal (note 19), p. 46.

145. Altmann (note 1), appendix A.7.

146. Lewer/Schofield (note 2), p. 12.

147. 5 mm/s is the threshold for "architectural" damage, and was discussed as safe limit for intermittent vibrations. Residential buildings in good condition should stand 10 mm/s. "Minor damage" occurs above 50-60 mm/s: A. C. Whiffin, D. R. Leonard, "A survey of traffic-induced vibrations," RRL Report LR 418 (Crowthorne Berkshire: Road Research Laboratory 1971), p. 14, table 4.

148. With grassy soil this maximum value occurs typically around several times ten Hz; at different frequencies, it may be 5-10-fold lower. See: J. M. Sabatier et al., "Acoustically induced seismic waves," *Journal of the Acoustical Society of America* 80, no. 2 (1986): 646-649; Altmann/Blumrich (note 80); W. Kaiser, *Sound and Vibration from Heavy Military Vehicles - Investigations of Frequency Assignment and Wave Spreading with respect to Monitoring under Disarmament Treaties* (Hagen: ISL, 1998).

149. "Non-lethal devices slice across science spectrum," *National Defense* (October 1993): 25, quoted after: Arkin (note 12).

150. Note that modern industrial buildings without plaster can stand earthquakes with soil vibrations of 20-40 mm/s: Whiffin/Leonard (note 147).

151. Lewer/Schofield (note 2), p. 12.

152. Vomiting: "Non-lethality ..." (note 2); Evancoe (note 18); Kiernan (note 16); Morehouse (note 2). Uncontrolled defecation or diarrhoea: Kiernan (note 16), Toffler/Toffler (note 12), p. 187; bowel spasms: "Non-lethality ..." (note 2); Morehouse (note 2).

153. High audio frequencies: Allen et al. 1948 (note 90); ultrasound: Parrack 1952 (note 91); H. O. Parrack, "Effect of Air-borne Ultrasound on Humans," *International Audiology* 5 (1966): 294-307; W. I. Acton, M. B. Carson, "Auditory and Subjective Effects of Airborne Noise from Industrial Infrasound Sources," *British Journal of industrial Medicine* 24 (1967): 297-304.

154. Dickson/Chadwick (note 63).

155. Parrack 1966 (note 153).

156. Mohr et al. (note 58).

157. E.g. with whole-body-exposed awake guinea pigs and monkeys: D. E. Parker, "Effects of Sound on the Vestibular System," ch. 7 in Tempest (note 53).

158. Gavreau et al. 1966 (note 54), p. 9.

159. Mohr et al. (note 58). Note that testicular aching (a different potentially embarrassing effect) of one subject was reported here.

160. See note 157.

161. Section 5.3 in: M. J. Griffin, *Handbook of Human Vibration* (London etc.: Academic, 1990).

162. Lumsden (note 13), p. 203.

163. Mohr et al. (note 58).

164. SARA (note 12). For *vibration*-induced gastrointestinal hemorrhages, on the other hand, see the sub-section on low-frequency vibration.