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Abstract

Acoustic weapons are under research and development in a few countries. Advertised as one type of non-lethal weapons, they are said to immediately incapacitate opponents while avoiding permanent physical damage. Reliable information on specifications or effects is scarce, however. The present report 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 loss 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 in balance, 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, sirens and whistles are the most likely sources. Powered, e.g., by combustion engines, these can produce tens of kilowatts of acoustic power at low frequencies, and kilowatts at high frequencies. Up to megawatt power is possible using explosions. For directed use the size of the source needs to be on the order of 1 meter, and proportionately-sized power supplies would be required.

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, sawtooth form, with unusually high propagation losses if the sound pressure is as high as required for marked effects on humans. Achieving sound levels that would produce aural pain, balance 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 for 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.

Preface

This study was begun during a one-month research stay in November 1997 at the Peace Studies Program of Cornell University, Ithaca NY, USA. It was finished in spring 1998 at Experimentelle Physik III, Dortmund University, Germany.

I should like to thank the Peace Studies Program of Cornell University, in particular Judith Reppy, for inviting me as a guest researcher. I am also grateful to the John D. and Catherine T. MacArthur Foundation, Chicago IL, USA, for providing the funds for the Technical Arms Control Project of the Peace Studies Program which financed my stay at Cornell University, and to the Ministry of Science and Research of the State of Nordrhein-Westfalen, Germany for granting funds to Universität Dortmund for a project on preventive arms control for new weapons technologies under which I finished this study. Finally, thanks go to Franz Fujara of Experimentelle Physik 3, Universität Dortmund, for acting as an applicant and supporting scientific-technical research of disarmament problems.

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1. Introduction[1]

1.1 Acoustic Weapons as Part of "Non-lethal" Weapons

Since the early 1990s there has been an increasing interest—mainly in the United States—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 analyses 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 prevent or reduce deaths, e.g., in a police context

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[1] A condensed version of this report appears in J. Altmann, "Acoustic Weapons—A Prospective Assessment," *Science and Global Security*, 1999.

[2] Most of the information on non-lethal weapons comes from journalistic articles in the defense or general press. The following articles and books give an overview of various problems of non-lethal weapons and provide many references: R. Span, J. Altmann, G. Hornig, T. Krallmann, M. Rosario Vega Laso, and 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), pp. 367-86; S. Aftergood, "The Soft-Kill Fallacy," *Bulletin of the Atomic Scientists* (September/October 1994), pp. 40-45; A. Roland-Price, "Non-Lethal Weapons: A Synopsis," in "Improving the Prospects for Future International Peace Operations—Workshop Proceedings," U.S. Congress, Office of Technology Assessment, OTA-BP-ISS-167 (Washington, DC: U.S. Government Printing Office, September 1995); J. Altmann, "'Non-Lethal' Weapons," 46th Pugwash Conference on Science and World Affairs, Lahti, Finland, 2-7 September 1996 (to be published in *Security, Cooperation and Disarmament: The Unfinished Agenda for the 1990s* [Singapore: World Scientific]) M. Dando, *A New Form of Warfare—The Rise of Non-Lethal Weapons* (London and Washington: Brassey's, 1996); N. Lewer and S. Schofield, *Non-Lethal Weapons: A Fatal Attraction? Military Strategies and Technologies for 21st-Century Conflict* (London and Atlantic City, NJ: 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 October 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, and T. Baines, "Weapons of Mass Protection—Nonlethality, Information Warfare, and Airpower in the Age of Chaos," Airpower Journal 9 (1) (Spring 1995), pp. 15-29; D.A. Morehouse, *Nonlethal Weapons—War Without Death* (Westport, CT and London: Praeger, 1996).

For a balanced view from inside the U.S. military, see J.W. Cook, III, D.P. Fiely, and M.T. McGowan, "Nonlethal Weapons—Technologies, Legalities, and Potential Policies," *Airpower Journal* 9 (Special Issue) (1995), pp. 77-91.

NLW developments for law-enforcement purposes are presented in considerable detail, e.g., in J. Alexander, D.D. Spencer, S. Schmit, and B.J. Steele (eds.), *Security Systems and Nonlethal Technologies for Law Enforcement* Proc. SPIE 2934 (1997).

[3] Morehouse (note 2).

[4] E.g.: A.W. Debban, "Disabling Systems: War-Fighting Option for the Future," *Airpower Journal* 7 (1) (Spring 1993), pp. 44-50; Roland-Price (note 2).

(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 United States that pushes 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.

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[5] It seems that other Western industrialized countries are taking 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 including directed-energy weapons and an acoustic bullet. See: Kokoski (note 2), p. 373; M. T., "Russians Continue Work on Sophisticated Acoustic Weaponry," *Defense Electronics* 26 (3) (March 1994), p. 12.

[6] These considerations may have been among the motives in the recent rethinking by the United States 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 United States 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 (1) (September 1995); text of the Protocol in *Trust and Verify*, no. 62 (London: Verification Technology Information Centre, November/December 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 was banned in 1995; see note 6.

[9] See also B. Starr, "Non-lethal Weapon Puzzle for US Army," *International Defense Review* no. 4 (1993), pp. 319-20.

As one general example of such promises note the statement:[10] "The scientists involved in the development of these [NLW] 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 counter-measures by opponents.

Since NLW comprise many very different technologies, an in-depth analysis is needed for each type of weapon.[11] The present report 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.

1.2 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 *lethal* use over some distance unrealistically high source powers (see 2.2.3.3 below).[12]

With respect to *non-lethal* use of low-frequency sound, a 1969 book on riot control already 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.[13] The only sound device discussed in some detail, the "Curdler" or "People Repeller," was said to emit a shrieking, pulsating sound that, amplified by a 350-W amplifier, produced 120 dB at 10 m distance.[14]

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[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, and J.-P. Stroot (eds.), *Verification After the Cold War—Broadening the Process* (Amsterdam: VU Press, 1994).

[12] N. Broner, "The Effects of Low Frequency Noise on People—A Review," *Journal of Sound Vibration* 58 (4) (1993), pp. 483-500; O. Backteman, J. Köhler, and L. Sjöberg, "Infrasound—Tutorial and Review: Part 4." *Journal of Low Frequency Noise and Vibration* 3 (2) (1984), pp. 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.

[13] R. Applegate, *Riot Control—Materiel and Techniques* (Harrisburg, PA: Stackpole, 1969), p. 273.

[14] Applegate (note 13), pp. 271-73. 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 C. Ackroyd, K. Margolis, J. Rosenhead, and T. Shallice, *The Technology of Political Control*, 2nd ed. (London: Pluto, 1980), p. 223-24.

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.[15] 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) that would then combine in the ear to form

Table 1
Selected examples of alleged properties, effects, and targets of acoustic weapons from the available literature.[16]

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)	17
Infrasound from non-linear superposition of two ultrasound beams (tested in Great Britain)	Intolerable sensations	Riot control	18
Infrasound	Incapacitation, disorientation, nausea, vomiting, bowel spasms; effect ceases when generator is turned off, no lingering physical damagee	Crowd/riot control, psychological operations	19
Very low frequency noise	Disorientation, vomiting fits, bowel spasms, uncontrollable defecation	Enemy troops	20

[15] Johnston (note 12), quoted in Broner (note 12). For the use of white noise on prisoners see also M. Lumsden, "Anti-personnel Weapons" (Stockholm/London: SIPRI/Taylor&Francis, 1978) and references given there.

[16] Additional sources not included in the table: B. Starr, "USA Tries to Make War Less Lethal," *Jane's Defence Weekly* (31 October 1992), p. 10; A. Toffler and H. Toffler, *War and Anti-War. Survival at the Dawn of the 21st Century* (Boston: Little, Brown and Co., 1993) (here: ch. 15, "War Without Bloodshed?") (quoted after the German translation: "Überleben im 21. Jahrhundert" [Stuttgart: DVA, 1994]); A.W. Debban, "Disabling Systems—War-Fighting Option for the Future," *Airpower Journal* 7 (1) (Spring 1993), pp. 44-50; Alexander (note 2); J. Barry and T. Morganthau, "Soon, 'Phasers on Stun'," *Newsweek* (7 February 1994), pp. 26-28; Kokoski (note 2); S. Aftergood, "The Soft-Kill Fallacy," *Bulletin of the Atomic Scientists* (September/October 1994), pp. 40-45; G. Frost and 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 ff.; Dando (note 2), pp. 11 ff; SARA report of 10 February 1995 (revised 13 February 1996); and other references as reported by W. Arkin, "Acoustic Anti-personnel Weapons: An Inhumane Future?" *Medicine, Conflict and Survival* 14 (4) (1997), pp. 314-26.

[17] Lumsden (note 15), pp. 203-05.

[18] "Army Tests New Riot Weapon," *New Scientist* (20 September 1973), p. 684; Ackroyd et al. (note 14), pp. 224-25. See also R. Rodwell, "'Squawk Box' Technology," *New Scientist* (20 September 1973), p. 667.

[19] "Non-lethality" (note 2).

[20] V. Kiernan, "War Over Weapons That Can't Kill," *New Scientist* (11 December 1993), pp. 14-16.

Sound Source	Effects	Targets	Ref
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		21
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	22
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	23
Very-low frequency acoustic bullet, emitted from antenna dishes, being investigated at ARDEC		Offensive capability against personnel in bunkers or vehicles	24
High-power, very low frequency acoustic bullets from 1-2 m antenna dish	Incremental effects from discomfort to death		25
High-frequency, non-diffracting (i.e., non-penetrating) acoustic bullet creates plasma in front of target	Blunt-object trauma		23
Baseball-sized acoustic pulse, about 10 Hz, over hundreds of meters, developed in Russia	Selectable from non-lethal to lethal levels		26
"Deference tone" at intersection of two otherwise inaudible beams, developed in Russia			26

[21] Lewer and Schofield (note 2), pp. 8 ff.

[22] P.R. Evancoe, "Non-Lethal Technologies Enhance Warrior's Punch," *National Defense* (December 1993), pp. 26-29.

[23] M. Tapscott and K. Atwal, "New Weapons That Win Without Killing On DOD's Horizon," *Defense Electronics* (February 1993), pp. 41-46.

[24] Starr (note 9).

[25] "Army Prepares for Non-Lethal Combat," *Aviation Week & Space Technology* (24 May 1993), p. 62.

[26] M.T. (note 5).

ARDEC: U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, USA
LANL: Los Alamos National Laboratory, Los Alamos, NM, USA
SARA: Scientific Applications and Research, Huntington Beach, CA, USA

The literature rarely gives sources. 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).

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 by annoying rather than by physical damage, they will not be further discussed here.

1.3 Actual Developments

The U.S. 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 program.[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

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[27] "Army Tests" (note 18); Ackroyd et al. (note 14), pp. 224-25. See also "'Squawk Box' Technology" (note 18).

[28] In a subsequent press conference, the British Army instead presented the 350-W amplifier/speaker system (see note 13) 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), p. 730.

[29] Ackroyd et al. (note 14), pp. 224-25.

[30] M. Bryan and W. Tempest, "Does Infrasound Make Drivers Drunk?" *New Scientist* (16 March 1972), pp. 584-86; R. Brown, "What Levels of Infrasound Are Safe?" *New Scientist* (8 November 1973), pp. 414-15; H.E. von Gierke and D.E. Parker, "Infrasound," ch. 14 in W.D. Keidel and W.D. Neff (eds.), *Auditory System—Clinical and Special Topics, Handbook of Sensory Physiology*, vol. V/3 (Berlin: Springer-Verlag, 1976), section VII.

[31] Starr (note 9).

[32] Tapscott and Atwal (note 23). See also http://www.pica.army.mil/pica/products/tbiwc.html.

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 "deference 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 blastwave type trauma at above 170 dB (for an explanation of the level unit decibel see section 1.5 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 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 U.S. embassies under siege, for crowd control, for barriers at perimeters or borders, for area denial or area attack, to incapacitate soldiers or workers.

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[33] Starr (note 9). See also http://www.sara.com/documents/future.htm. Similar information is provided by Tapscott and Atwal (note 23); 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 of 10 February 1995 (revised 13 February 1996) and other references as reported by Arkin (note 16).

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

In Germany, Daimler-Benz Aerospace (DASA), Munich, did 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.[38] Recently, a German Fraunhofer Institute was tasked to develop a prototype and test the deterring effect of strong sound.[39]

1.4 Goals of This Report

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.[40] A very recent article is significantly more comprehensive, but relies heavily on general statements from a firm engaged in developing acoustic weapons, the defense 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.[41]

The present report 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.[42]

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

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[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. Tens of meters are more realistic; see appendix A.5.

[37] Note that the infrasound research seems to have been refocused recently; see J. Hecht, "Not a Sound Idea," *New Scientist* 161 (2178) (20 March 1999), p. 17.

[38] 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, Konzeptbeschreibungen akustischer Wirkmittel, pp. 307-333 in J. Müller et al., *Nichtletale Waffen, Abschlußbericht*, Band II, Dasa-VA-0040-95=OTN-035020, Daimler-Benz Aerospace, 30.4.1995.

[39] A. Dähn, "Angriff auf das Trommelfell," *Berliner Zeitung*, 24 March 1999.

[40] Lumsden (note 15); L. Liszka, "Sonic Beam Devices—Principles," pp. 89-91 in Report on "Expert Meeting on Certain Weapon Systems and on Implementation Mechanisms in International Law," Geneva, 30 May-1 June 1994 (Geneva: International Committee of the Red Cross, July 1994).

[41] Arkin (note 16).

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

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 (1.5) gives a few general remarks on acoustics. Effects of strong sound on humans are described in section 2. Section 3 deals with production of strong sound. Protective measures and therapy are the subject of section 4. Several allegations made in journalistic articles are analyzed in section 5. Finally, section 6 presents preliminary conclusions. General properties of pressure waves in air are described in the appendix, and details of the analysis of allegations concerning acoustic-weapons effects are given.

1.5 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 report 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 fig. 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

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

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

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

are chosen. These values are about the human hearing threshold at 1 kHz, close to the frequency of highest sensitivity. Under normal conditions the acoustic impedence of air is 400 kg/(m^2s). Using this value in eq. (A-6) yields an I_{rms} equal to I_{ref}.[43] Levels will usually refer to these values in this report; 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 the appendix. For sound pressures that 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.[44] However, for the sake of completeness, because of the smooth transition from one to the other, and because blast waves have been mentioned in this context,[45] strong shock is included into the present considerations.

2. Effects of Strong Sound on Humans

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 (2.1). In the following parts, special emphasis is put on low frequencies (2.2) 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 (2.3) and ultrasound (2.4) are covered rather briefly. A special subsection treats shock waves, e.g., from explosive blasts (2.5).

Table 9 at the end of section 2 gives a simplified summary of the various effects in the different frequency ranges.

2.1 General Remarks on the Ear

2.1.1 Hearing and Hearing Damage

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

[44] For a discussion of blast weapons, see, e.g., ch. 6 in Lumsden (note 15).

[45] SARA (note 16).

In the human ear (fig. 1),[46] 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 that 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 (see 2.1.2).[47]

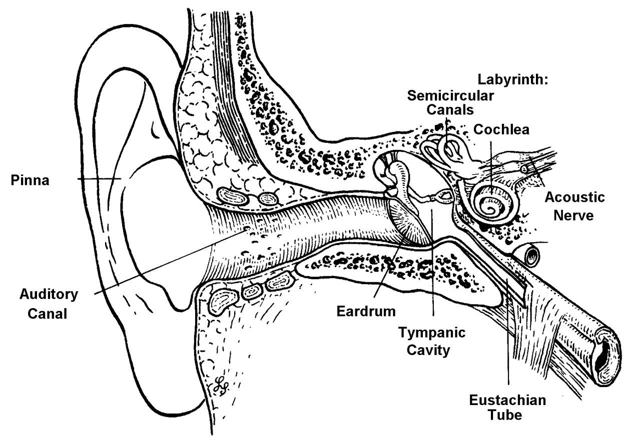

Fig. 1 The human ear consists of three parts: external, middle, and inner ear. Sound waves reflected by the pinna and travelling in the auditory canal produce vibration of the eardrum (tympanic membrane). The three middle-ear ossicles (malleus, incus, and stapes) transfer this motion—increasing the pressure—to 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

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[46] H.-G. Boenninghaus with T. Lenarz, "Hals-Nasen-Ohrenheilkunde für Studierende der Medizin," 10. Aufl., (Berlin: Springer, 1996).

[47] For much more detailed descriptions see, e.g., W.D. Keidel and W.D. Neff (eds.), "Auditory System—Anatomy, Physiology (Ear)," *Handbook of Sensory Physiology*, vol. V/1 (Berlin: Springer-Verlag, 1974).

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. 46, used by permission of authors and publisher; original copyright: Springer-Verlag).

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.[48] 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.[49] 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 loss, remain. Because this so-called "noise-induced hearing damage" is somehow cumulative, exposure criteria have to include the duration and recovery time in addition to 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 cannot 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),[51] but also dogs, monkeys, and—for blast waves—sheep have been used.

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[48] Karl D. Kryter, "The Effects of Noise on Man" (New York: Academic Press, 1970, 1985), ch. 1; W. Melnick, "Hearing Loss from Noise Exposure," ch. 18 in C.M. Harris (ed.), *Handbook of Acoustical Measurements and Noise Control* (New York: McGraw-Hill, 1991).

[49] A.R. Møller, "The Acoustic Middle Ear Muscle Reflex," in Keidel and Neff (note 47).

[50] Note that PTS can accumulate over a long time even if recovery from TTS occurs daily; see Kryter 1985 (note 48), pp. 271 ff. For a discussion of different approaches to exposure criteria see: Kryter 1970 (note 48), chs. 5, 6; Kryter 1985 (note 48), ch. 7; H.E. von Gierke and W.D. Ward, "Criteria for Noise and Vibrations Exposure," ch. 26 in Harris (note 48).

[51] For chinchillas and cats a sensitivity higher by 18 dB has been mentioned by W.D. Ward, "Noise-Induced Hearing Damage," ch. 45 in M.M. Paparella et al. (eds.), *Otolaryngology*, 3rd ed., vol. II (Philadelphia: Saunders, 1991); for guinea pigs, Ward reports similar susceptibility as for humans, whereas Eldredge assumed 20 to 25 dB higher sensitivity: D.H. Eldredge, "Clinical Implications of Recent Research on the Inner Ear," *Laryngoscope* 70 (4) (April 1960), pp. 373-81.

Which noises will produce more PTS (for higher level and/or longer duration) can be pre dicted on the basis of the TTS.[52] 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.[53] 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. 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.[54] 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."[55] 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 fibers may degenerate.[56] Details cannot be covered here; some aspects of short exposures to high levels will be mentioned in the following sections.

Fig. 2 shows the human hearing threshold and curves of equal perceived loudness from very low to high frequencies.[57] 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:

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[52] Kryter 1970 (note 48), chs. 5 and 6; Kryter 1985 (note 48), ch. 7; Melnick (note 48); B. Berglund and P. Hassmén, "Sources and effects of low-frequency noise," *Journal of the Acoustical Society of America* 99 (5) (May 1996), pp. 2985-3002, and literature cited there.

[53] Kryter 1970, 1985 (note 48).

[54] See, e.g.: Kryter 1970, 1985 (note 48); K. D. Kryter, "Impairment to Hearing From Exposure to Noise," *Journal of the Acoustical Society of America* 53 (5) (May 1973), pp. 1211-34, and the following discussion (pp. 1235-52); D. Henderson et al. (eds.), *Effects of Noise on Hearing* (New York: Raven, 1976); R.A. Schmiedt, "Acoustic Injury and the Physiology of Hearing," *Journal of the Acoustical Society of America* 76 (5) (November 1984), pp. 1293-1317; J.C. Saunders et al., "The Anatomical Consequences of Acoustic Injury: A review and Tutorial," *Journal of the Acoustical Society of America* 78 (3) (September 1985), pp. 833-60, and five-year update, 90 (1) (July 1991), pp. 136-46; Melnick (note 48); Ward 1991 (note 51); H.-G. Dieroff, "Mechanisms of Noise-induced Injuries of the Inner Ear," *Proceedings of the International Symposium on "Noise and Disease,"* Schriftenreihe des Vereins für Wasser-, Boden- und Lufthygiene no. 88 (Stuttgart and New York: G. Fischer, 1993), pp. 238-49.

[55] Note that sometimes also long-term injury comes under this heading, and damage from short exposure is called *acute* acoustic trauma. See, e.g, B. Kellerhals, "Acute Acoustic Trauma," *Advances in Oto-Rhino-Laryngology* 27 (1981), pp. 114-20.

[56] Ward 1991 (note 51).

[57] 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. See, e.g., A.M. Small, Jr. and R.S. Gales, "Hearing Characteristics," ch. 17 in Harris (note 48).

- 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).[58]
- Aural pain—this occurs above about 140 dB (200 Pa) throughout the audio region.[59] 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.[60] 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 (42-55 kPa peak).[61] For rupture due to a pressure pulse, e.g., from an explosion see 2.5 below. 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.[62]

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[58] Melnick (note 48); Kryter 1970 (note 48), ch. 4. For the discomfort threshold see also S.R. Silverman, "Tolerance for Pure Tones and Speech in Normal and Defective Hearing," *Annals of Otology, Rhinology and Laryngology* 56 (3) (September 1947), 659-77.

[59] Melnick (note 48); Kryter 1970 (note 48), ch. 4. For the pain threshold see also Silverman (note 58). At a slightly lower threshold there is a tickling sensation in the ear.

[60] v. Gierke and Parker (note 30).

[61] v. Gierke and Parker (note 30).

[62] F.G. Hirsch, "Effects of Overpressure on the Ear—A Review," *Annals of the New York Academy of Sciences* 152 (Art. 1) (1968), pp. 147-62 (here: pp. 155 ff.); Ward 1991 (note 51).

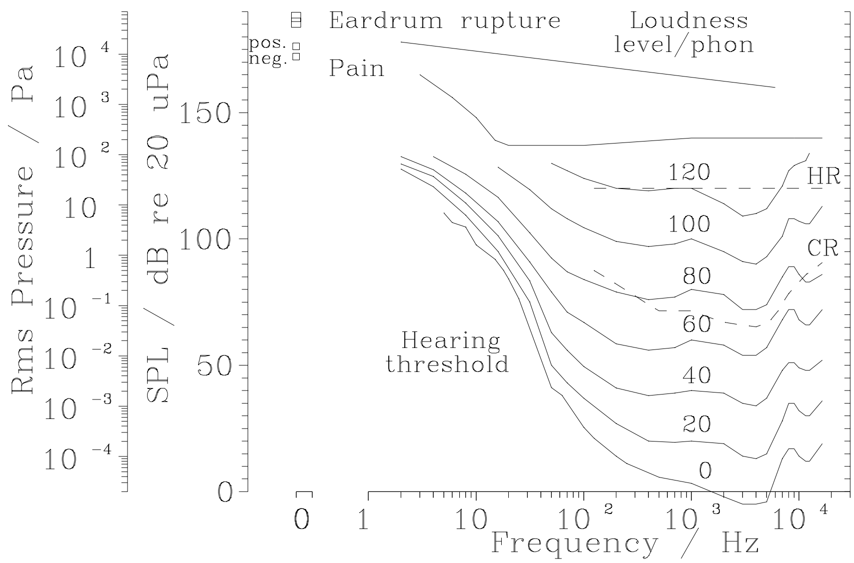

Fig. 2 Threshold of hearing (correspon ding to 0 phone), curves of equal perceived loudness for 20, 40, 60, 80, 100, and 120 phones, rms sound pressure (logarithmic scale) and its level versus frequency. The threshold values are for binaural hearing of pure tones; monaural perception thresholds are higher. 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.[63]

2.1.2 Vestibular System

[63] Binaural single-tone threshold 5-100 Hz (earphone exposure) from N.S. Yeowart and M.J. Evans, "Thresholds of audibility for very low-frequency pure tones," *Journal of the Acoustical Society of America* 55 (4) (April 1974), pp. 814-18. Also in N.S. Yeowart, "Thresholds of Hearing and Loudness for Very Low Frequencies," ch. 3 in W. Tempest (ed.), *Infrasound and Low Frequency Vibration* (London and New York: Academic Press, 1976), p. 50; above 100 Hz from Small and Gales (note 57). Binaural loudness curves 2-63 Hz (whole-body exposure) from H. Møller and J. Andresen, "Loudness of Pure Tones at Low and Infrasonic Frequencies," *Journal of Low Frequency Noise and Vibration* 3 (2) (1984), pp. 78-87; 100 Hz and above: Small and Gales (note 57). For summary presentations of additional measurements at low frequencies see, e.g., Berglund and Hassmén (note 52). Hearing loss hazard curves from Melnick (note 48). Pain threshold curves below 100 Hz are given in H.E. von Gierke and C.W. Nixon, "Effects of Intense Infrasound on Man," ch. 6 in Tempest (ibid.), p. 134; and v. Gierke and Parker (note 30), p. 604; above 100 Hz, e.g., in Small and Gales (note 57).

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).[64]

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.

2.2 Effects of Low-Frequency Sound

In the 1960s and 1970s there was a wave of articles ascribing exaggerated effects to infrasound, not only in the general press.[65] Much of this was anecdotal. In some cases, effects observed in one laboratory could not be reproduced in another, e.g., concerning the evocation of nystagmus (involuntary eye movements) by infrasound.[66] One reason may be production of harmonics in test systems. Harmonics need to be controlled carefully, otherwise—because the sensitivity increases rapidly with frequency—they could influence the results.

2.2.1 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

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[64] "Motion Sickness," ch. 7 in M.J. Griffin, *Handbook of Human Vibration* (London and San Diego: Academic Press, 1990).

[65] E.g., see the sensational article "The Low-Pitched Killer—Can Sounds of Silence Be Driving Us Silly," *Melbourne Sunday Press* (7 September 1975), reproduced in Broner (note 12); 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 center 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 15), p. 204. This obviously refers to Gavreau's work done at Marseille, see: V. Gavreau, R. Condat and H. Saul, "Infra-Sons: Générateurs, Détecteurs, Propriétés physiques, Effets biologiques," *Acustica* 17 (1) (1966), pp. 1-10; V. Gavreau, "Infrasound," *Science Journal* 4 (1) (January 1968), pp. 33-37.

[66] Infrasound-provoked nystagmus was reported by M.J. Evans, "Physiological and Psychological Effects of Infrasound at Moderate Intensities," ch. 5 in Tempest (note 63), but could not be reproduced in other experiments: D.E. Parker, "Effects of Sound on the Vestibular System," ch. 7 in Tempest (note 63); v. Gierke and Parker (note 30); H. Ising, F.B. Shenoda, and C. Wittke, "Zur Wirkung von Infraschall auf den Menschen," *Acustica* 44 (1980), pp. 173-81. See also D.E. Parker, R.L. Tubbs, and V.M. Littlefield, "Visual-field Displacements in Human Beings Evoked by Acoustical Transients," *Journal of the Acoustical Society of America* 63 (6) (June 1978), pp. 1912-18.

about 50 Hz the hearing threshold increases steeply.[67] It is often assumed that hearing below 20 Hz is due to non-linear production of harmonics in the middle ear.[68]

The strong increase of human sound sensitivity with frequency in the low-frequency region is evident in fig. 2. It is further important that the equal-loudness curves lie much closer at lower frequencies; this means that loudness perception increases much faster with sound pressure level here than at higher frequencies. Also the pain threshold is closer to the hearing threshold at low frequencies.

2.2.2 Low-Intensity Effects of Low-Frequency Sound

Effects of low levels of low-frequency sound are not relevant for weapons; they are mentioned here only for the sake of completeness.

Annoyance by infrasound has occurred at widely differing levels, from 120 dB inside motor vehicles to below 60 dB in neighborhoods affected by industry sources.[69] In a systematic study annoyance seemed related to the loudness sensation, however.[70] In some cases, indirectly-produced audible rattling noise may be a main reason for annoyance.[71] Stress hormones increased in rats after infrasound exposure to 100-120 dB; in humans, this occurred only when subjects had not slept.[72] Sleep was influenced somewhat by 80-100 dB low-frequency noise.[73] Some people seem to be more sensitive to low-frequency sound (and/or rattling noises) than others, which may lead to stronger physiological responses.[74]

Some of these effects can have long-term negative consequences on the well-being of the people affected, be it at the workplace or at home, in particular if the noise persists over long periods of time.

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[67] 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. See v. Gierke and Nixon (note 63), pp. 122 ff.

[68] For a discussion of this effect see v. Gierke and Parker (note 30), pp. 594 ff.

[69] M.E. Bryans, "Low Frequency Noise Annoyance," ch. 4 in Tempest (note 63); Berglund and Hassmén (note 52).

[70] H. Møller, "Annoyance of Audible Infrasound," *Journal of Low Frequency Noise & Vibration* 6 (1) (1987), pp. 1-17.

[71] Berglund and Hassmén (note 52); K. Nishimura et al., "The Pituitary Adrenocortical Response in Rats and Human Subjects Exposed to Infrasound," *Journal of Low Frequency Noise and Vibration* 6 (1) (1987), pp. 18-28.

[72] Nishimura et al. (note 71); K. Nishimura, "The Effects of Infrasound on Pituitary Adrenocortical Response and Gastric Microcirculation in Rats," *Journal of Low Frequency Noise and Vibration* 7 (1) (1988), pp. 20-33; Y. Yamasumi et al., "The Pituitary Adrenocortical Response in Rats Exposed to Fluctuating Infrasound," *Journal of Low Frequency Noise and Vibration* 13 (3) (1994), pp. 89-93.

[73] R. Inaba and A. Okada, "Study on the Effects of Infra- and Low Frequency Sound on the Sleep by EEG Recording," *Journal of Low Frequency Noise and Vibration* 7 (1) (1988), pp. 15-19.

[74] S. Yamada et al., "Physiological Effects of Low Frequency Noise," *Journal of Low Frequency Noise and Vibration* 5 (1) (1986), pp. 14-25.

2.2.3 High-Intensity Effects of Low-Frequency Sound

2.2.3.1 Effects 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.[75] It is likely that PTS observed, e.g., in people exposed to low-frequency noise at the workplace is mainly due to higher frequencies that are also present.

Table 2
Auditory effects of low-frequency sound

Frequency / Hz	Level / dB	Duration	Effect	Ref
<1-20	125-171	minutes	often TTS at audio frequencies, recovery within 1/2 hour	76
3 or 23	130	1 h	no TTS	77
low audible	90	many hours	TTS, recovery after up to 2 days	76
≤ 40	140-150	0.5-2 min	no PTS	78
Simulated airbag inflation:				79
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	

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75 v. Gierke and Parker (note 30); A.R. Møller, "Function of the Middle Ear," ch. 15 in Keidel and Neff (note 47).

76 Table II and references in v. Gierke and Nixon (note 63); Table 5 and references in v. Gierke and Parker (note 30); D. Johnson, "The Effects of High Level Infrasound," in: H. Møller and P. Rubak (eds.), Conference on Low Frequency Noise and Hearing, 7-9 May 1980, Aalborg, Denmark (also NTIS ADA 081792, used here); Table I and references in Berglund and Hassmén (note 52).

77 C. Mohr, J.N. Cole, E. Guild and H.E. von Gierke, "Effects of Low Frequency and Infrasonic Noise on Man," *Aerospace Medicine* 36 (9) (1965), pp. 817-24 (here p. 822); Kryter 1970 (note 48), p. 229.

78 Mohr et al. (note 77). During the exposures above 40 Hz subjects wore ear protection so that ear pressure levels were markedly below 150 dB.

79 H.C. Sommer and 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 and Parker (note 30), section V; D.L. Johnson, "Hearing Hazards Associated with Infrasound," pp. 407-21 in R.P. Hamernik, D. Henderson and R. Salvi (eds.), *New Perspectives on Noise-Induced Hearing Loss* (New York: Raven, 1982) (also as NTIS ADA 110374, used here). Note, however, that there are a few documented cases of PTS, tinnitus, and disequilibrium from real airbag deployment: J.E. Saunders et al., "Automobile airbag Impulse Noise: Otologic Symptoms in Six patients," *Otolaryngology—Head and Neck Surgery* 118 (2) (1998), pp. 228-34.

Sonic boom (mainly 2-20 Hz)	162-171 peak	seconds	no PTS	[80]

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. This may be due to negative pressure in the middle ear produced when the Eustachian tube opens only during the inward motion of the eardrum.[81] Ventilation of the middle ear via the valsalva operation—producing an overpressure in the mouth while holding one's nose and keeping the lips closed, which opens the Eustachian tubes from the nasal cavity and forces air into the middle ear—helps, but needs to be repeated constantly.

Even more impressive will be pain in the ear, which occurs at levels of 135 dB from 100 down to 50 Hz, slowly rising to 140 dB at 20 Hz and then fast increasing to about 162 dB at 2 Hz; for static pressure, pain sets in at 173-177 dB (see fig. 2).[82]

There seems to be only one example where long-term exposure to intense infrasound has produced permanent ear damage to humans: scars were observed on the eardrums of crew members of early German Diesel submarines.[83] In animals, on the other hand, damage has been produced. Chinchillas, which have much thinner eardrums than humans and are known to be much more sensitive in the audible range, were exposed to frequencies between 1 and 30 Hz at levels 150-172 dB. Among the effects observed were: thinning, bleeding, and rupture of the tympanic membrane; hydrops and rupture of the saccular wall; blood in the cochlear scalae; rupture of the round-window membrane; degeneration of hair cells.[84] With dogs and cats, less pathological damage was observed. Thirty seconds of exposure to 172 dB infrasound did not even produce reddening in a human eardrum.[85]

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 the two values.[86]

2.2.3.2 Effects on the Vestibular System

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[80] v. Gierke and Parker (note 30).

[81] v. Gierke and Nixon (note 63).

[82] v. Gierke and Nixon (note 63), p. 134; v. Gierke and Parker (note 30), p. 604.

[83] Johnson (note 76).

[84] D.J. Lim, D.E. Dunn, D.L. Johnson and T.J. Moore, "Trauma of the Ear from Infrasound," *Acta Otolaryngologica* (Stockholm) 94 (1982), pp. 213-31 (also NTIS ADA 121826, used here); Johnson (note 76).

[85] Lim et al. (note 84); the human experiment had been done by one of the authors before the chinchilla results were known.

[86] v. Gierke and Nixon (note 63); v. Gierke and Parker (note 30). 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, and D.H. Eldredge, "Hazards of Intense Sound and Ultrasound," *Annals of Otology, Rhinology, Laryngology* 58 (1949), pp. 732-38.

Vestibular excitation can be measured by reflexively produced eye movements (nystagmus) or, with humans, by performance in balancing tests. With guinea pigs, pressure transients produced eye and head movements from 160 dB; infrasound, however, failed to do so at pressure levels up to 172 dB. With monkeys, neither infrasound of up to 172 dB nor pressure transients of 54 kPa (189 dB) resulted in eye movements.[87] Reports on eye movements elicited in humans by infrasound from 2 to 20 Hz at threshold levels of 140 to 110 dB[88] could not be reproduced by several other studies at levels from 130 to 140 dB, 142 to 155 dB, or even 172 dB.[89]

Balancing tests with humans showed no infrasound effects at levels from 110 to 140 dB.[90] On the other hand, exposure to 150 to 155 dB at 50 to 100 Hz caused mild nausea and giddiness.[91] Marked effects were also observed with audio frequencies from 200 Hz to 2 kHz, starting at levels of 120 dB (see 2.3.2). Thus, the vertigo and nausea effects ascribed to intense infrasound in the journalistic articles cannot really be confirmed for that frequency range. In the audio range, however, such effects do exist.

2.2.3.3 Effects on the Respiratory Organs

With infrasound of 0.5 Hz, decrease or even cessation of active respiration in anesthetized dogs was observed above 165 and 172 dB (3.6 and 8.0 kPa). This is less dramatic than it sounds, however, since the slow strong pressure variation acts as artificial respiration. Normal respiration returned after the infrasound ended, and no adverse after-effects were observed.[92] 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.[93]

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.[94] Thus, the strongest respiratory effects will occur in the low audio range (50 to 100 Hz), at levels of about 150 dB (0.6 kPa) and above.

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[87] Parker, in Tempest (note 66).

[88] Evans (note 66). For a short discussion of the inconsistency see v. Gierke and Parker (note 30).

[89] Ising et al. (note 66); v. Gierke and Nixon (note 63); v. Gierke and Parker (note 30).

[90] v. Gierke and Nixon (note 63).

[91] Mohr et al. (note 77).

[92] v. Gierke and Nixon (note 63).

[93] Including "held breath" up to 167 dB (4.8 kPa); v. Gierke and Nixon (note 63).

[94] Mohr et al. (note 77).

Here it may be appropriate to take a short look at Broner's rough estimate for a deadly infrasound weapon mentioned in subsection 1.2.[95] He used a too low value of 6 to 10 kPa for lung rupture (see 2.5 below) and assumed non-directional propagation. Achieving this sound pressure on a sphere of 250 m radius means a total power—according to eqs. (A-6) and (A-7)—of $2\cdot10^{11}$ W, about 1000 times the sound power of a Saturn V rocket at launch. Even if this value could in principle be reduced by orders of magnitude by using a directed source, for infrasound wavelengths (e.g., λ=34 m at ν=10 Hz) its diameter would have to be unrealistically large, e.g., many hundreds of meters according to (A-13). Non-linear effects would have to be included, but the basic qualitative result remains valid (and holds similarly also for lower infrasound pressures for lesser effects) (see 5.1.1 below).

2.2.3.4 Other Effects

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. Two subjects suffered from transient headache, and one of these also from testicular aching. The visual field vibrated and acuity was reduced. Speech sounds were modulated, but there was no significant decrease in intelligibility. Subjects showed marked fatigue after exposure. Brief infrasound had no effect on visual acuity, on the other hand.[96] Also, motor tasks and speech production were not influenced.[97]

2.2.4 Vibration Considerations

It is sometimes maintained that infrasound sets organs in motion similarly to external vibration applied to the body.[98] Whereas there are similarities, there are also important differences.

2.2.4.1 Effects of Whole-Body Vibration

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 the greatest discomfort is caused; sometimes the head moves strongest at about 4 Hz. The voice may warble at 10 to 20 Hz, and eye resonances within the head may be responsible for blurred vision between

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[95] Broner (note 12).

[96] Mohr et al. (note 77).

[97] Mohr et al. (note 77).

[98] Section VII.B. in v. Gierke and Parker (note 30); e.g., Gavreau et al. 1966 (note 65).

15 and 60 Hz.[99] In-phase movement of all organs in the abdominal cavity with consequent variation of the lung volume and chest wall is responsible for the resonance at 4-6 Hz.[100]

Vibration above 2 Hz produces several physiological effects (cardiovascular, respiratory, endocrine, etc.) that are important for judging comfort, e.g., in travel and work. In the present context, more drastic effects are of interest. In a variety of studies, humans have experienced accelerations of 15 m/s^2 to 100 m/s^2 amplitude with frequencies between 1 and 25 Hz (note that the gravity acceleration at sea level is g=9.8 m/s^2). They suffered, inter alia, from dyspnoea, chest and periumbilical pain, and under some conditions gastrointestinal bleeding. The subjective tolerance was reached at 35 m/s^2 at 1 Hz, 20 m/s^2 from 4 to 8 Hz, and 65 m/s^2 at 20 Hz. No lasting effects were observed.[101]

2.2.4.2 Vibration Due to Low-Frequency Sound[102]

Air pressure variations impinging on the human body produce some vibration, but due to the large impedance mismatch nearly all energy is reflected. 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.[103] 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.

2.3 Effects of High-Intensity High-Frequency Audio Sound

2.3.1 Effects on Ear and Hearing

As stated, there is a vast amount of literature on hearing damage due to noise in the audio region. PTS is mainly seen and studied for occupational exposure over a decade and more, from weighted levels of below 80 dB(A) to usually less than 120 dB(A).[104] The sensitivity to TTS and PTS follows roughly the loudness contours. Long-term-exposure PTS is usually strongest, and

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[99] Section 2.2 in Griffin (note 64).

[100] Section VII.B. in v. Gierke and Parker (note 30); see also: H. von Gierke, "Biodynamic Response of the Human Body," *Applied Mechanics Review* 17 (12) (December 1964), pp. 951-58; H. von Gierke, "Response of the Body to Mechanical Forces," *Annals of the New York Academy of Sciences* 152 (Art. 1) (1968), pp. 172-86.

[101] Section 5.3 in Griffin (note 64), and references quoted there.

[102] See note 100.

[103] 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.

[104] Kryter 1970 (note 48); Melnick (note 48).

develops fastest, at 4 kHz, then in the range 3 to 6 kHz, relatively independent of the noise spectrum at the workplace.

In the present context, however, the questions relate to short exposures at potentially higher levels. With respect to effects desired by weapons designers, one should recall that throughout the audio range, discomfort begins at about 120 dB, and pain occurs above about 140 dB.[105]

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 results with humans that show that short exposures at high levels need not produce PTS. At high audio frequencies, humans are much less susceptible than around 1 kHz.

Table 3
Auditory effects of high-frequency audio sound on humans

Frequency / kHz	**Level / dB**	**Duration**	**TTS**	**PTS**	**Remarks**	**Ref**
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		106
0.25-5.6	up to > 140	many seconds		obviously none	testing for tickle and pain thresholds	107
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	108

105 Silverman (note 58); Small and Gales (note 57).

106 H. Davis et al., report from 1943; summary in H. Davis et al., "Temporary Deafness Following Exposure to Loud Tones and Noise," *Laryngoscope* 56 (1) (January 1946), pp. 19-21. Several quantitative results are shown in Kryter 1970 (note 48), figs. 127, 129, 137, and Kryter 1973 (note 54), figs. 10, 11; note that for 0.5 kHz Kryter's figures 129 resp. 11 show durations from about 64 to about 188 minutes, whereas Davis et al.'s summary speaks only of "periods from one to 64 minutes."

107 Silverman (note 58). Above 130 dB, the level was increased every 1.5 s by 1 dB until the subject felt and announced tickle or pain; the latter was often not reached at the highest possible level. Six sessions were done, with an interval of one week. In these, the thresholds of discomfort, tickle, and pain were determined separately and usually twice. Before and after a session normally the threshold of acuity (hearing threshold) was measured. These results are not explicitly mentioned, but the stated aim ("to determine what effect exposure to high intensity stimuli might have on the threshold of acuity") makes clear that there was nothing significant to report.

108 Sommer and Nixon (note 79); Johnson (note 79); see also Ward 1991 (note 51). Note ear damage in a few cases: Saunders et al. 1998 (note 79).

Jet afterburner noise	> 140	seconds at a time		no consistent PTS after several months	flight-deck/ airfield ground personnel	109
9-15	140-156	5 min	TTS at exposure frequencies and half of those, fast recovery	none		110

Table 4
PTS and physiological damage produced by high-frequency audio sound in animals

Animal	Frequency / kHz	Level / dB	Duration	PTS	Physiological damage	Ref
Chinchilla		~ 120	~ 1 h		damage to hair cells, etc.	111
Guinea pig	0.19-8.0	135-140	few minutes		severe hair cell injury	112
		> 140	few minutes		organ of Corti destroyed at respective most-affected site	
Cat	0.125	150	4 h	none		113
		153-158	4 h	partially/fully deaf	hair cell	
	1.0	120	1 h	none	losses	
		130	1 h	55 dB at 2 kHz	in general	
		140	1 h	deaf at all frequencies	parallel to	
	2.0	140	1 h	deaf at ≥ 2 kHz	functional	
	4.0	135	1 h	none	deficiencies	
		140	1 h	60 dB at 4 kHz		

Table 4 shows the results of PTS experiments on animals. With the cat experiments, at all frequencies a 10-dB increase marked the transition from minimal to severe destruction in the cochlea.

Acoustic trauma for short exposures occurs above some critical combination of level and duration that corresponds to a kind of "elastic limit" of the organ of Corti. In chinchilla and

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[109] W.D. Ward, "Hearing of Naval Aircraft Maintenance Personnel," *Journal of the Acoustical Society of America* 29 (12) (December 1957), pp. 1289-1301; H. Davis, "Effects of High-Intensity Noise on Naval Personnel," *U.S. Armed Forces Medical Journal* 9 (7) (July 1958), pp. 1027-48. Nevertheless, hearing losses, some considerable, were found among noise-exposed persons.

[110] H.O. Parrack, "Effect of Air-borne Ultrasound on Humans," *International Audiology* 5 (1966), pp. 294-307.

[111] Saunders et al. 1985 (note 54); Schmiedt (note 54).

[112] H. Davis and Associates, "Acoustic Trauma in the Guinea Pig," *Journal of the Acoustical Society of America* 25 (6) (November 1953), pp. 1180-89; see also Eldredge (note 51).

[113] T.R. Dolan, H.W. Ades, G. Bredberg, and W.D. Neff, "Inner Ear Damage and Hearing Loss After Exposure to Tones of High Intensity," *Acta Otolaryngologica* (Stockholm) 80 (1975), pp. 343-352.

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. In the chinchilla, one critical combination is 120 dB for 7 minutes; in the guinea pig, 135 dB holds for 7 minutes.[114]

Public-warning sirens in the United States are limited to 123 dB(C) at the ground.[115] For near-daily exposure of humans over 10 years to pure tones of 1.5 minutes duration or shorter, accepting PTS of less than 10 dB at ≤1 kHz, 15 dB at 2 kHz, and 20 dB at ≥ 3 kHz for at least 50% of the exposed people, a damage curve has been estimated: for frequencies up to 330 Hz, a level of 130 dB holds, decreasing to 122 dB at 1.6 kHz and further to 115 dB at 3 kHz, then increasing again to 125 dB at 7 kHz.[116] For the maximum instantaneous sound pressure occurring in an isolated event during a working day, 200 Pa (140 dB) has been given.[117]

Assuming the same squared-intensity-duration law as observed with chinchillas and guinea pigs 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 seconds exposure to 140 dB, 4 seconds to 145 dB, and 0.4 seconds to 150 dB. The latter combination fits to the simulated-air-bag experiments (0.4 s, 153 dB) of table 3.[118] 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); there is one documented case of a small rupture after about 5 minutes exposure to about 158 dB at 6.5 kHz.[119] Again it should be noted that a ruptured eardrum transmits less energy to the inner ear and may thus reduce permanent damage there.[120]

2.3.2 Non-Auditory Effects

Vestibular responses elicited by audio sound were found in deaf human subjects at levels of 120-130 dB (at 200-500 Hz), about 140 dB (at 1 kHz), and 145-160 dB (at 2 kHz).[121] In nor-

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114 Ward 1991 (note 51) and references cited there. A non-linear combination like this is of course different from the equal-energy concept, where the same damage would be expected for constant product of intensity times duration.

115 G.D. Tepper and P.L. Schaumberg, "Public Notification System Aided by Actual Measurements of Siren Coverage," *IEEE Transactions on Power Apparatus and Systems* PAS-102 (9) (September 1983), pp. 3184-88.

116 Kryter 1970 (note 48), fig. 103.

117 v. Gierke and Ward (note 50).

118 Ward 1991 (note 51).

119 Davis et al. (note 86).

120 See note 62.

121 H.W. Ades et al., three reports of 1953, 1957, and 1958, quoted in Parker, in Tempest (note 66). See also fig. 267 in Kryter 1970 (note 48).

mal-hearing subjects, visual-field motion from 125 dB tones occurred in 50% of the subjects at 500 and 1000 Hz.[122] Balancing tests showed first performance decreases already at 95 or 105 dB at audio frequencies, e.g., 590 Hz; however, in a later repetition, no effect was found.[123] At levels about 140 dB near jet engines, a sense of disturbance in the equilibrium may be felt. Ground maintenance personnel described the effects as mild dizziness and unsteadiness; nausea did not occur during exposure, but sometimes after it. They did not take the symptoms seriously. When the analyzing scientist stood at certain positions near the intake a "most unpleasant and disturbing sensation of general instability and weakness was experienced at the critical speed." Nausea, true dizziness, visual disturbances, or nystagmus were not observed. The symptoms were immediately blocked—or did not occur in the first place—when the ears were protected. The critical engine rotation rates differed between people, but were between 5000 and 7000 min^{-1}. The sound spectra had maxima at 1.6 to 6.5 kHz with levels from 120 to 130 dB.[124] 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. One reason may be that ultrasound as a then-debated cause had been laid to rest, another that the symptoms did not often occur under comparable circumstances.[125] In the present context it is particularly relevant that the phenomenon seemed to occur at different resonance frequencies for different people; whether one of the spectral peaks was responsible and if so, which one, is unclear.

Acoustic stimulation of the equilibrium sense occurs at unusually low levels when the bone wall of a vestibular canal has a defect, creating a weak site that increases lymph motion under pressure from the inner ear.[126]

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[122] Parker et al. 1978 (note 66).

[123] C.S. Harris et al., three reports of 1968, 1971, and 1972, quoted in Parker, in Tempest (note 66); see also: v. Gierke and Parker (note 30); Kryter 1985 (note 48), pp. 450 ff. and references cited there.

[124] E.D.D. Dickson and D.L. Chadwick, "Observations on Disturbances of Equilibrium and Other Symptoms Induced by Jet Engine Noise," *Journal of Laryngology and Otology* 65 (1951), pp. 154-65.

[125] Dickson and Chadwick (note 124) seems to be the only article that 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, see: L.L. Kopra, "Hearing Loss among Air Force Flight-Line Personnel," *Journal of the Acoustical Society of America* 29 (12) (December 1957), pp. 1277-83; Ward 1957 (note 109); Davis 1958 (note 109). In the second edition of 1985 Kryter still referred to Dickson and Chadwick of 1951 (note 124) when discussing equilibrium disturbances by jet noise: Kryter 1985 (note 48), p. 451. For articles citing Dickson and Chadwick (note 124) see, e.g.: B.F. McCabe and M. Lawrence, "The Effects of Intense Sound on the Non-Auditory Labyrinth," *Acta Oto-Laryngologica* (Stockholm) 49 (1958), pp. 147-57; D.E. Parker, H.E. von Gierke, and M. Reschke, "Studies of Acoustical Stimulation of the Vestibular System," *Aerospace Medicine* 39 (December 1968), pp. 1321-25; and A. Man, S. Segal, and L. Naggan, "Vestibular Involvement in Acoustic Trauma (An Electronystagmographic Study)," *Journal of Laryngology and Otology* 94 (December 1980), pp. 1395-1400.

Among the personal communications reported by Dickson and Chadwick (note 124) without further references is that one experimenter suffered from immediate headache as long as his ears were exposed to "153 phons" at 12-18 kHz, together with pain in the stomach and a slight feeling of nausea.

[126] L.J. Roggeveen and H.A.E. van Dishoeck, "Vestibular Reactions as a Result of Acoustic Stimulation," *Practica Oto-Rhino-Laryngologica* 18 (4) (1956), pp. 205-13; see also: Kryter 1985 (note 48), p. 451; G. Lange, "Das Tullio-Phänomen und eine Möglichkeit seiner Behandlung," *Archiv f. klinische und experimentelle Ohren-, Nasen- und*

Nystagmus could be produced in non-anesthetized guinea pigs at levels from 142 dB to 169 dB of frequencies between 500 Hz and 2 kHz.[127] Severe lesions up to collapse were observed in the vestibular organs of guinea pigs after minutes of exposure to audio sound in the 136 to 163 dB region.[128] In monkeys, 140 to 145 dB at 500 Hz elicited consistent eye movements.[129]

At audio frequencies and lower levels (90 to 125 dB), many studies have found short-term physiological reactions of the startle-response type, including muscle tension, slightly increased heart rate, constriction of skin blood vessels, and eye pupil dilation, with some effects showing habituation with continuing stimuli.[130] Near jet engines at up to 139 dB, several vegetative reactions were observed, such as variations of skin temperature and humidity, and of finger pulse.[131]

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 above 120 dB.[132] Close to a 165 dB sound source, the experimenters often had a tickling sensation in the mouth and nose.[133]

At levels of 160 dB and higher, heating becomes relevant. When, in tests of the small siren mentioned in 3.2 below, a hand was put into the beam with 200 W acoustic power at 7 kHz (level 165 dB), strong heating due to high friction was felt between fingers held close together, but not touching; the effect vanished if the fingers were opened. With 2 kW power, increasing heat was felt in the central lobe of the beam on the palm of the hand; cotton burnt within a few

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Kehlkopfheilkunde (Arch. oto-rhino-laryngol.) 187 (2) (1966), pp. 643-49, and references cited there; and A. Shupak et al., "Vestibular Findings Associated with Chronic Noise Induced Hearing Impairment," *Acta Otolaryngologica* (Stockholm) 114 (1994), pp. 579-85, and references cited there.

[127] M.F. Reschke, "High-intensity, Audio-frequency Vestibular Stimulation in the Guinea Pig," unpublished Doctoral Dissertation (Dept. of Psychology, Miami University, Oxford, OH), quoted after Parker, in Tempest (note 66).

[128] McCabe and Lawrence (note 125); P.L. Mangabeira-Albernaz, W.P. Covell, and D.H. Eldredge, "Changes in the Vestibular Labyrinth with Intense Sound," *Laryngoscope* 69 (12) (December 1959), pp. 1478-93. The organ of Corti in the inner ear was of course injured as well by these exposures.

[129] Parker, in Tempest (note 66).

[130] G. Jansen, "Physiological Effects of Noise," ch. 25 in Harris (note 48).

[131] G. Jansen, "Influence of High Noise Intensities on the Human Organism" (in German), *Wehrmedizinische Monatsschrift* no. 10 (1981), pp. 371-79.

[132] Davis et al. (note 86).

[133] C.H. Allen, H. Frings, and I. Rudnick, "Some Biological Effects of Intense High Frequency Airborne Sound," *Journal of the Acoustical Society of America* 20 (1) (January 1948), pp. 62-65; see also C.H. Allen and I. Rudnick, "A Powerful High Frequency Siren," *Journal of the Acoustical Society of America* 19 (5) (September 1947), pp. 857-65.

seconds.[134] The difference can be explained by the amount of sound absorption: whereas it is small on naked skin due to the impedance mismatch, it becomes strong wherever strong friction impedes the air movement, as in textiles, hair, or narrow ducts. With the more powerful siren, experimenters at times observed a loss of the sense of equilibrium or slight dizziness, even when wearing ear protection. Whether an unusual fatigue observed after a day of working with the siren was due to the sound or general stress was unclear.[135] 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.[136]

2.4 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.[137]

2.4.1 Auditory Effects

The upper threshold of hearing varies between subjects and decreases with age.[138] Although airborne ultrasound (above 20 kHz) can elicit aural effects because of bone conduc-

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[134] Allen and Rudnick (note 133); Allen et al. 1948 (note 133). For the killing of furred rodents by overheating with audio sound of levels above 150 dB, see section 2.4.2.

[135] Allen et al. 1948 (note 133). Davis et al. (note 86) estimated that a sense of touch due to resonances in the partially open mouth, in nasal cavities, or the sinuses would begin already at 120 dB.

[136] 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: D.J. Orchik et al., "Intensity and Frequency of Sound Levels from Cordless Telephones. A Pediatric Alert," *Clinical Pediatry Philadelphia* 24 (12) (1985), pp. 688-90; J.P. Guyot, "Acoustic Trauma Caused by the Telephone. Report of Two Cases," *ORL Journal of Otorhinolaryngology and Related Spec.* 50 (5) (1988), pp. 313-18; R.H. Beastall, "Acoustic Trauma in a Telephone Operator," *Occupational Medicine Oxford* 42 (4) (1992), pp. 215-16; and P.M. McMillan and P.R. Kileny, "Hearing Loss From a Bicycle Horn," *Journal of the American Academy of Audiology* 5 (1) (1994), pp. 7-9 (all cited after Medline abstract). On the other hand, there are many articles about damage due to impulse noise of levels of 150 dB and more; see 2.5.

[137] H.O. Parrack, "Ultrasound and Industrial Medicine," *Industrial Medicine and Surgery* 21 (4) (April 1952), pp. 156-64; Parrack 1966 (note 110); W.I. Acton and M.B. Carson, "Auditory and Subjective Effects of Airborne Noise from Industrial Infrasound Sources," *British Journal of Industrial Medicine* 24 (1967), pp. 297-304; W.I. Acton, "A Criterion for the Prediction of Auditory and Subjective Effects Due to Air-borne Noise from Ultrasonic Sources," *Annals of Occupational Hygiene* 11 (1968), pp. 227-34; W.I. Acton, "The Effects of Industrial Airborne Ultrasound on Humans," *Ultrasonics* 12 (May 1974), pp. 124-28.

[138] Small and Gales (note 57).

tion,[139] it 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 the ultrasound ones of 21, 24, 26, and 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.[140]

Considering the non-linear production of sub-harmonics observed in electrophysiological recordings from guinea pigs and chinchillas, which occurred at levels of 110-130 dB, an extension of damage-risk criteria to the ultrasound region was proposed: the level of 110 dB in the third-octave bands around 20 kHz, 25 kHz, and 31.5 kHz should not be transcended during the 8-hour working day.[141]

2.4.2 Non-Auditory Effects

In an analysis of ultrasonic washers and drills, where workers in the vicinity had experienced fatigue, headaches, tinnitus, and nausea, it turned out that there were considerable levels of sound at audible frequencies as well. Together with laboratory experiments, the conclusion was that the effects are caused by these audible frequencies.[142] The article reporting the threshold shift tests at up to 154 dB referred to in 2.3.1 made no mention of vestibular effects; since, even close to jet engines, ultrasound levels were below 100 dB, these could not be the cause of the equilibrium disturbances observed by personnel.[143] Respiratory effects are again not to be expected because of the fast pressure changes.

At extreme levels, close to the siren of maximum 160-165 dB, tickling in mouth and nose was observed with ultrasound as with high-frequency audio sound.[144] For such levels, as with high audio frequencies, heating will occur mostly in narrow passages and other places of high friction. Above about 160 dB, heating will be felt on naked skin as well. For bare skin at 20 kHz, an absorbed-intensity ratio of below 10^{-3} was measured; theoretically, then, total immersion in an ultrasound field above 180 dB would be required to overheat a human body to death after more

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[139] The sensation exists even for frequencies up to 100 kHz, see, e.g., H.G. Dieroff and H. Ertel, "Some Thoughts on the Perception of Ultrasonics by Man," *Archive of Oto-Rhino-Laryngology* 209 (1975), pp. 277-90. The sensed frequency is in the 10 kHz region and arises probably in the inner ear, see Kryter 1985 (note 48), p. 462 and references cited there. Diagnostic and therapeutical ultrasound is usually in the Megahertz region and is coupled via a viscous fluid.

[140] Parrack 1966 (note 110).

[141] Acton 1968 (note 137); this limit is also referred to in v. Gierke and Ward (note 50). Note that the author later proposed to reduce the limit at 20 kHz to 75 dB, because the one-third-octave band centered there contains frequencies audible to a portion of the population: W.I. Acton, "Exposure Criteria for Industrial Ultrasound," *Annals of Occupational Hygiene* 18 (1975), pp. 267-68.

[142] Acton and Carson (note 137); Acton 1968, 1974 (note 137).

[143] Parrack 1952 (note 137); Parrack 1966 (note 110). The loss of equilibrium and dizziness from 160-165 dB at 20 kHz quoted by Acton 1974 (note 137) on p. 125 (contrary to p. 124) had actually been described as occurring from *audible* high-frequency sound close to the source, but not in the beam, by the original authors, see Allen et al. 1948 (note 133).

[144] Allen et al. 1948 (note 133).

than 50 minutes.[145] On the other hand, the absorption ratio of rat fur is above 0.2, and thus lethal overheating should occur in 10 minutes of 155-158 dB. In fact, rats and mice were killed by 148-158 dB in 40 to 10 minutes at audio frequencies (where fur absorption is lower) between 1 and 15 kHz; at 20 kHz with 160-165 dB they died in one minute. At the latter level, shaved animals survived about three times longer. In all cases the cause of death was too high body temperature.[146]

2.5 Impulse-Noise and Blast-Wave Effects

There are several circumstances where sound is neither tonal nor of a steady wide- or narrow-band-noise character, but occurs in pulses. The most obvious example is with shooting, especially in the military. But also in industry impulsive noise occurs, e.g., with drop forges or shooting of mounting bolts into walls. Table 5 gives several examples of such impulse noise. 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.

Another kind of sources is explosion accidents or terrorist bombings, where overpressures can reach many times the normal atmospheric pressure. At such pressures, not only will the ear be damaged, but severe injury to other organs will occur as well, with consequence up to death. Among these organs the lung is the most sensitive one. Of course it would be more than inappropriate to label a blast-wave weapon producing such bodily damage an "acoustic" weapon. However, as mentioned in subsection 1.5, since there is a smooth transition between such intensities and those correctly called acoustic, and because blast waves have been mentioned in this context, such effects will be included here.

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**	**Ref**
Drop forge	0.11	135	147
Shooting bolts into walls, 80 cm	0.63	150	148

[145] These rough estimates were done for bare skin and do not include the heating occurring in clothing or hair. On the other hand, the cooling mechanism of the human body was neglected as well.

Of course ultrasound coupling into the human body is much stronger if occurring via a liquid medium, as in diagnostics or in therapy, where even focused shock waves are used to destroy stones.

[146] Allen et al. 1948 (note 133); Parrack 1952 (note 137); Parrack 1966 (note 110). Insects were also killed in 10-120 seconds.

[147] Kryter 1985 (note 48), fig. 7.27.

[148] H.G. Dieroff, "Gehörschädigender Impulslärm," *Zeitschrift für die gesamte Hygiene* 20 (4) (April 1974), pp. 215-18.

8 toy pistol types, 50 cm	0.63-2.0	150-160	149 150
3 toy paper-cap gun types, 30 cm	0.89	153	
8 firecracker types, 3 m	0.063-63	130-190	149
Sonic boom low-flying aircraft (N wave)	2.4-6.9	162-171	151
Pistol	5.0	168	152 153
Rifle	1.7	159	154
4 rifles	1.78-8.43	159-173	
Automatic rifle	7.2	171	152
Field cannon 105	50.3	188.0	152
17 Pdr. T/A gun	54	188.6	153
3 inch mortar short	58	189.2	153

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 of high intensities and the total energy to which the ear is exposed. In such a way shots within closed rooms can achieve characteristics of longer noise bursts like those produced by some industrial equipment.[155]

2.5.1 Auditory Effects

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 further over 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

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[149] D. Gupta and S.K. Vishwakarma, "Toy Weapons and Firecrackers: A Source of Hearing Loss," *Laryngoscope* 99 (March 1989), pp. 330-34. See also G. Fleischer et al., "Kinderknallpistolen und ihre Wirkung auf das Gehör," *HNO* 46 (9) (1998), pp. 815-20.

[150] L.B. Poche, Jr., C.W. Stockwell, and H.W. Ades, "Cochlear Hair-Cell Damage in Guinea Pigs after Exposure to Impulse Noise," *Journal of the Acoustical Society of America* 46 (4, pt. 2) (1969), pp. 947-51.

[151] v. Gierke and Parker (note 30).

[152] A. Salmivalli, "Military Audiological Aspects in Noise-Induced Hearing Losses," *Acta Otolaryngologica* (Stockholm), Supplementum 360 (1979), pp. 96-97.

[153] N.E. Murray and G. Reid, "Temporary Deafness due to Gunfire," *Journal of Laryngology and Otology* 61 (1946), pp. 92-130.

[154] K.D. Kryter and G.R. Garinther, "Auditory Effects of Acoustic Impulses from Firearms," *Acta Otolaryngologica* (Stockholm), Supplementum 211 (1965), pp. 1-22.

[155] In such case not only the so-called A duration of the first overpressure pulse has to be considered, but also the B duration, which ends when the pressure magnitude has decreased to 10% of its peak value (-20 dB in level).

more than with continuous noise.[156] This is demonstrated in the first entries of table 6, which shows TTS and PTS data from humans. Ear pain occurred for most subjects exposed to pulses of 2 ms duration if the peak overpressure was above 0.36 kPa (145 dB).[157] On the other hand, there are cases when both eardrums were ruptured, but nevertheless the patients did not suffer from pain.[158] Table 7 gives results from animal experiments. With impulse noise, TTS often increased in the first hours after exposure.

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. A peak level of 162 dB (2.5 kPa) has been given as a criterion for short impulses 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; this would not cause excessive hearing loss in 75% of the exposed people. To protect the most sensitive persons as well, 10 dB should be subtracted. For incidence on the ear from the side, the limit should be lowered by 5 dB. If only occasional single impulses occur, 10 dB could be added. For durations below 3 ms, the limiting peak pressure increases—faster than proportionally—with the inverse duration.[159]

With blast waves from explosions, overpressures can become markedly higher, and damage to the ear occurs more often. 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.[160] Note, however, that in experiments with incidence from the side rupture has already been observed at about 15 kPa (178 dB), resulting in about 50 kPa (188 dB) at the eardrum by reflection.[161]

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

Peak level / dB	Pulse duration	Number of pulses	TTS	PTS	Remarks	Ref
140	2 ms	75	40 dB at 4 kHz	none	most sensitive subject	157
155	2 ms	75	< 40 dB at 4 kHz	none	least sensitive subject	

[156] R.R.A. Coles et al., "Hazardous Exposure to Impulse Noise," *Journal of the Acoustical Society of America* 43 (2) (1968), pp. 336-43.

[157] W.D. Ward, W. Selters, and A. Glorig, "Exploratory Studies on Temporal Threshold Shift from Impulses," *Journal of the Acoustical Society of America* 33 (6) (June 1961), pp. 781-93.

[158] A. Shupak et al., "Vestibular and Audiometric Consequences of Blast Injury to the Ear," *Archive of Otolaryngology, Head and Neck Surgery* 119 (December 1993), pp. 1362-67.

[159] Coles et al. (note 156).

[160] Hirsch (note 62).

[161] D.R. Richmond et al., "Physical Correlates of Eardrum Rupture," *Annals of Otology, Rhinology & Laryngology* 98 (5, pt. 2, Suppl. 140) (May 1989), pp. 35-41.

159 189 180-183	rifle shots gun shots blank shot		30-80, recovery in up to 6 days	none	marksman position gun-crew position ear near rifle muzzle	**162**
186-189	3" mortar	first shot second shot after 80 min.	max. 75 dB at 5.8 kHz recovery up to 5.8 kHz in 2 months	 50 dB at 8.2 and 9.7 kHz	monaural exposure: pain, tinnitus eardrum rupture, bleeding	162
Firecracker 0.5 m from ear		1		60-80 dB at ≥ 3 kHz	male student	**163**
150-160 at 0.5 m 130-190 at 3 m	toy weapons firecrackers		with 2-5% of population (600)	with 2.5% of population, mean 29 dB at 4 kHz	village festival in India	**164**
162-171	40-400 ms	many		none	sonic-boom N waves	**165**

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.[166]

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**	**Ref**

[162] Murray and Reid (note 153); G. Reid, "Further Observations on Temporary Deafness Following Exposure to Gunfire," *Journal of Laryngology and Otology* 61 (December 1946), pp. 609-33.

[163] W.D. Ward and A. Glorig, "A Case of Firecracker-Induced Hearing Loss," *Laryngoscope* 71 (12) (December 1961), pp. 1590-96.

[164] Gupta and Vishwakarma (note 149). See also Fleischer (note 149).

[165] v. Gierke and Parker (note 30).

[166] For a review see R.H. Chait, J. Casler, and J.T. Zajtchuk, "Blast Injury of the Ear: Historical Perspective," *Annals of Otology, Rhinology & Laryngology* 98 (5, pt. 2, Suppl. 140) (May 1989), pp. 9-12. Note that two other articles of the same special issue on "Effects of Blast Overpressure on the Ear" contain additional historical references: Y.Y. Phillips et al., "Middle Ear Injury in Animals Exposed to Complex Blast Waves Inside an Armored Vehicle," ibid., pp. 17-22; and M. Roberto, R.P. Hamernik, and G.A. Turrentine, "Damage of the Auditory System Associated with Acute Blast Trauma," ibid., pp. 23-34. For an example describing effects from a bomb in Belfast, see A.G. Kerr and J.E.T. Byrne, "Concussive Effects of Bomb Blasts on the Ear," *Journal of Laryngology and Otology* 89 (2) (February 1975), pp. 131-43. A more recent study is Shupak et al. 1993 (note 158).

Rhesus monkey	168	2	60 µs pos., 100 ms neg. press.	33 dB median at 14 kHz	some		167
		10-20 more			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	168
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	169

In animals, eardrum rupture from blasts has been studied for decades. Peak overpressures for 50% incidence for dogs, sheep, pigs, and monkeys are in the range of 80-200 kPa (192-200 dB), similarly as for humans.[170] With pigs and sheep exposed to the complex, reverberating, long-

[167] G.A. Luz et al., "The Relation between Temporary Threshold Shift and Permanent Threshold Shift in Rhesus Monkeys Exposed to Impulse Noise," *Acta Oto-laryngologica* (Stockholm), Supplement 312 (1973), pp. 5-15; V.M. Jordan et al., "Cochlear Pathology in Monkeys Exposed to Impulse Noise," ibid., pp. 16-30; M. Pinheiro et al., "The Relation Between Permanent Threshold Shift and the Loss of Hair Cells Monkeys Exposed to Impulse Noise," ibid., pp. 31-40.

[168] R.P. Hamernik, J.H. Patterson, and R.J. Salvi, "The Effect of Impulse Intensity and the Number of Impulses on Hearing and Cochlear Pathology in the Chinchilla," *Journal of the Acoustical Society of America* 81 (4) (April 1987), pp. 1118-29. For cochlear damage due to impulses of narrow-band noise see J.H. Patterson, Jr. et al., "An Isohazard Function for Impulse Noise," *Journal of the Acoustical Society of America* 93 (5) (May 1993), pp. 2860-69. See also J.H. Patterson and R.P. Hamernik, "Blast Overpressure Induced Structural and Functional Changes in the Auditory System," *Toxicology* 121 (1) (July 25, 1997), pp. 29-40.

[169] Poche et al. (note 150).

[170] Since the 1950s, atmospheric nuclear tests were used for that purpose, too. Laboratory experiments using shock tubes are being continued, as are field experiments using live ammunition. See: Hirsch (note 62); Roberto et al. (note 166); Richmond et al. (note 161); Phillips et al. (note 166); and the respective references.

duration waveform inside an armored vehicle penetrated by a shaped charge, middle-ear ossicles were fractured or disrupted in about 50% of the ears exposed to above 100 kPa peak pressure (194 dB).[171]

2.5.2 Non-Auditory Effects

Vestibular effects of impulse noise were observed with humans as well as with animals. Guinea pigs exposed to 90-300 rifle shots at 1.4-1.8 kPa peak overpressure (157-159 dB) showed not only severe damage in the cochlear organ of Corti, but also a varying degree of lesions in the vestibular end organs, the character of which generally resembled those in the cochlea. However, the animals had not shown marked signs of vestibular disturbance.[172] In soldiers suffering from hearing loss due to exposure to firearms, vestibular disturbances were found, using nystagmus and body sway; there are, however, several ways of compensating for a loss of vestibular-organ sensitivity.[173] Among the victims of bomb blasts, permanent vestibular damage could be found even if vertigo and balance problems had improved.[174]

The organ second most sensitive to blast is the lung, along with the upper respiratory tract.[175] 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. In sheep, these occur—with 5 exposures—at overpressures from 53 kPa (188 dB peak level) for durations above 5 ms, and higher pressures at shorter durations; with 100 exposures, the threshold value was 32 kPa (184 dB). In humans, who should be less sensitive, no abnormities were found after exposure to 12 blasts of 24 kPa (182 dB) and 8-9 ms duration.[176] With higher pressures, however, large hemorrhages form not only in the tracheae, but also in the lungs, due to contusion. Tissue tears may lead to large-scale bleeding or edema in the lungs and to air emboli, which eventually can cause death by suffocation or obstruction of blood vessels.[177]

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[171] Phillips et al. (note 166).

[172] J. Ylikoski, "Impulse Noise Induced Damage in the Vestibular End Organs in the Guinea Pig—A Light Microscopic Study," *Acta Otolaryngologica* (Stockholm) 103 (1987), pp. 415-521.

[173] J. Ylikoski et al., "Subclinical Vestibular Pathology in Patients with Noise-Induced Hearing Loss from Intense Impulse Noise," *Acta Otolaryngologica* (Stockholm) 105 (1988), pp. 558-63; Shupak et al. 1994 (note 126).

[174] Shupak et al. 1993 (note 158). These are cases where vestibular disturbances occurred without head trauma; see also Kerr and Byrne (note 166).

[175] Recently there are indications that under certain conditions the gastrointestinal tract is equally or even more sensitive than the lung. For this and damage to further organs see M.A. Mayorga, "The Pathology of Primary Blast Overpressure Injury," *Toxicology* 121 (1) (July 25, 1997), pp. 17-28.

[176] K.T. Dodd et al., "Nonauditory Injury Threshold for Repeated Intense Freefield Impulse Noise," *Journal of Occupational Medicine* 32 (3) (March 1990), pp. 260- 66.

[177] Mayorga (note 175). For a discussion of various forms of lung damage see also A.J. Januszkiewicz, T.G. Munde, and K.T. Dodd, "Maximal Exercise Performance-Impairing Effects of Simulated Blast Overpressure in Sheep," *Toxicology* 121 (1) (July 25, 1997), pp. 51-63.

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.[178] Exposed to 20-64 impulses of 2-10 ms duration, no lung injury was found in sheep as long as the peak overpressure remained below 100 kPa (194 dB).[179]

Estimates of overpressures for human lung damage and death are given in table 8.

Table 8
Severe damage to humans by strong-shock waves

<table>
<tr><th>Damage</th><th>Threshold overpressure / kPa</th><th>Overpressure for 50% incidence / kPa</th><th>Overpressure for 100% incidence / kPa</th></tr>
<tr><td>Eardrum rupture</td><td></td><td></td><td></td></tr>
<tr><td>fast rising, duration 3 and 400 ms</td><td>35</td><td>105</td><td></td></tr>
<tr><td>slowly rising/static</td><td>42-55</td><td>~150</td><td></td></tr>
<tr><td>Lung rupture</td><td></td><td colspan="2">"severe"</td></tr>
<tr><td>duration 3 ms</td><td>260-340</td><td colspan="2">680</td></tr>
<tr><td>duration 400 ms</td><td>83-103</td><td colspan="2">260</td></tr>
<tr><td>Death</td><td></td><td></td><td></td></tr>
<tr><td>duration 3 ms</td><td>770-1100</td><td>1100-1500</td><td>1500-2100</td></tr>
<tr><td>duration 400 ms</td><td>260-360</td><td>360-500</td><td>500-690</td></tr>
</table>

Effects 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.[180] Note that normal atmospheric pressure is 101 kPa corresponding to 194 dB peak level.

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[178] K.T. Dodd et al., "Cardiopulmonary Effects of High-Impulse Noise Exposure," *Journal of Trauma: Injury, Infection, and Critical Care* 43 (4) (October 1997), pp. 656-66. See also N.M. Elsayed, "Toxicology of Blast Overpressure," *Toxicology* 121 (1) (July 25, 1997), pp. 1-15.

[179] P. Vassout et al., "Extra-Auditory Effects of Single and Multiple Blasts," in R. Brun and L.Z. Dumitrescu (eds.), *Shock Waves @ Marseille III* (Berlin: Springer, 1995), pp. 425-28.

[180] Overpressure values from: Hirsch (note 62); v. Gierke and Parker (note 30); C.S. White, "The Scope of Blast and Shock Biology and Problem Areas in Relating Physical and Biological Parameters," *Annals of the New York Academy of Sciences* 152 (Art. 1) (1968), pp. 89-102. See also: D.R. Richmond et al., "The Relationship between Selected Blast-Wave Parameters and the Response of Mammals Exposed to Air Blast," ibid., pp. 103-21; I.G. Bowen et al., "Biophysical Mechanisms and Scaling Procedures Applicable in Assessing Responses of the Thorax Energized by Air-Blast Overpressures or by Nonpenetrating Missiles," ibid., pp. 147-62; and J.H. Stuhmiller, "Biological Response to Blast Overpressure: A Summary of Modeling," *Toxicology* 121 (1) (July 25, 1997), pp. 91-103.

Knocking a person down, which occurs with nuclear blasts of 0.5 to 1 s duration at 7-10 kPa overpressure (171-174 dB), is not relevant for shock waves from conventional explosions.[181] In the latter case, durations 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 eardrum, the lungs) would be more relevant (see 5.1.4 and A.7).

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).

Range / subsection	**Frequency / Hz**	**Ear pain**	**PTS from short exposure**	**Ear-drum rupture**	**Transient vestibular effects**	**Respiratory organs**
Infrasound 2.2	1-20	160 .. 140 (1 .. 20 Hz)	none up to 170	> 170	none up to 170	none up to 170
Low audio 2.2	20-250	135-140	none up to 150	160	150 mild nausea	150 intolerable sensations
High audio 2.3	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 2.3 / 2.4	8 k-0 k > 20 k	140	none up to 156	?	none up to 154	140 tickling in mouth, etc. 160 heating
Blast wave 2.5	-	145	150-160	185	160	200 lung rupture 210 death

Note that the levels are approximate, that the effects change smoothly with frequency and depend on duration, and that there is wide individual variability. For details, see the respective subsections in the text and the references given there. k: kilo (1000).

3. Production of Strong Sound

Whereas sources of audio sound are well known, much less is known for sources of low-frequency sound, and in particular of infrasound, which occurs at surprisingly high levels in every-day life. Thus several low-frequency sources are described in 3.1. Strong sources potentially usable for weapons are the subject of 3.2.

3.1 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

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181 Overpressure value for the case of a large explosion of long duration from G.F. Kinney and K.J. Graham, *Explosive Shocks in Air*, 2nd ed. (New York: Springer-Verlag, 1985), table XV.

—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 (see 2.2.3.1) 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

$$\Delta p = \rho_W \; g \; \Delta h \tag{4}$$

(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.[182] 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_A 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. As described in A.4, 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).

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 the plate to the ear defender of a headset. Thus, levels up to 140 dB (400 Pa) were achieved.[183]

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 wavelengths larger than the chamber dimension. One chamber working with six 0.46-m loudspeakers

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[182] For this and the following examples see also Johnson (note 76).

[183] N.S. Yeowart, M.E. Bryan, and 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), pp. 335-42; see also Evans (note 66).

achieved 140 dB (200 Pa).[184] However, speakers provide only limited travel (1 cm or less) of their membranes. Stronger pressure variation is possible with pistons. For example, the Dynamic Pressure Chamber built at the Wright-Patterson Air Force Base in Ohio 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.[185]

It is interesting to consider what the same piston would achieve when working into free air. With a large baffle, a motion amplitude of 6 cm at 10 Hz according to eq. (A-10) would result in an equivalent spherical source of only 82 Pa rms pressure (132 dB) at 1 m radius; at 1 Hz, 0.82 Pa (92 dB) would remain. 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	186
Thunder at 1 km	< 4-125	< 114	187
Wind fluctuations	~ 1	up to > 160	o.c.
Running	< 2	95	188
Blowing into another's ear	~ 0.5	170	188
Diving to 2 m of water	~ 1	180	188
Wind turbine, 150 m downwind	2-10	80	189
Ventilation/air conditioning	1-20	60-90	189

184 N.S. Yeowart, M.E. Bryan, and W. Tempest, "Low-frequency Noise Thresholds," *Journal of Sound and Vibration* 9 (1969), pp. 447-53; see also v. Gierke and Nixon (note 63).

185 D.L. Johnson, "Various Aspects of Infrasound," in L. Pimonow (ed.), *Colloque international sur les infra-sons* (Paris: Center National de Recherche Scientifique, 1974), pp. 129-53, cited after v. Gierke and Parker (note 30). Figure 2 in v. Gierke and Nixon (note 63) shows "piston stroke 12 cm d.a."; the total piston travel can be estimated from the amplitude $\Delta x = \gamma V \Delta p/(Ap)$ with $\Delta p = 11.3$ kPa $= 2^{1/2} \cdot 8.0$ kPa amplitude, $V = 1.56$ m^3, and $A = 2.6$ m^2, γ between 1 (isothermal) and 1.4 (adiabatic process in air) to be between 10 and 20 cm.

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

187 R.D. Hill, "Thunder," ch. 11 in R.H. Golde (ed.), *Lightning*, vol. 1 (London and New York: Academic Press, 1977).

188 Johnson (note 76); own calculations.

189 Backteman et al. (note 12); Berglund and Hassmén (note 52).

Source	Dominant frequency range / Hz	Sound pressure level / dB	Ref.
Industry	5-100	70-110	190
In car (window closed)	5-100	100	190
In car (window open)	1-30	120	190
Jet aircraft (underneath flight path at airport)	10-sev. 1000	135	191
Jet engine with afterburner (at runway margin)	20-800	148	192
Large rocket, crew compartment	10-2000	135	193
Large rocket at 1.6 km	1-200	130	194
Sonic booms	1-100	120-160	195
Airbag inflation	~ 5 / 500-1000	170	196
Ship engine room		133	197
Blast wave	< 1-100	unlimited	
Loudspeaker headset	1-200	146	183
Whole-body chamber, loudspeakers	2-100	140	184
Whole-body chamber, piston	0.5-10/30	172/158	185

3.2 Acoustic Sources Potentially Usable for Weapons

Strong sounds can of course be produced by *loudspeakers* connected to amplifiers.[198] 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,

[190] Backteman et al. (note 12).

[191] Johnson (note 76); v. Gierke and Nixon (note 63).

[192] From own measurements of MiG-21 and Tornado fighter-bombers, see: J. Altmann and R. Blumrich, "Acoustic and Seismic Signals during Aircraft Take-offs and Landings" (in German), pp. 417-20 in *Fortschritte der Akustik—DAGA 94* (Bad Honnef: DPG-GmbH., 1994); and R. Blumrich, *Sound Propagation and Seismic Signals of Aircraft used for Airport Monitoring—Investigations for Peace-keeping and Verification* (Hagen: ISL, 1998).

[193] Mohr et al. (note 77); v. Gierke and Parker (note 30).

[194] v. Gierke and Nixon (note 63).

[195] v. Gierke and Nixon (note 63); v. Gierke and Parker (note 30).

[196] Sommer and Nixon (note 79); Johnson (note 76).

[197] H.G. Leventhall, "Man-made Infrasound—Its Occurrence and Some Subjective Effects," in Pimonow (note 185), quoted after v. Gierke and Nixon (note 63).

[198] For general articles on loudspeaker arrays see the special issue of *Journal of the Audio Engineering Society Audio/Acoustics/Applications* 38 (4) (April 1990).

because of the membrane-air impedance mismatch.[199] Better efficiencies (10 to 50%) are possible with (exponential or other) horns in front of the speaker, which also improve directivity. For low frequency, the horns have to be large.[200]

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.

Table 11
Strong sound sources potentially usable for acoustic weapons.

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	201
Small siren	0.3	3 k-0 k	2	165	close	202 203
Large air-flow-modulation speaker	2.3	10-500	20	126	27	204
Giant whistle	0.2	40-200	several	160	close	206
Hartmann whistle	0.2	4 k-8 k 20 k	2 0.6	160	close	207
Piezoelectric transducer with disk	0.2	20 k	0.2	160	close	208 209
Explosive blast		< 1-100	unlimited	unlimited		
Hypothetical repetitive blast	1	100	1 M	180	close	o.c.

The values given are typical or apply to a specific device (notional for the hypothetical repetitive-blast device). k: kilo (1000), M: Mega (1,000,000); 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.

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 that 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, as expected from the diffraction of the 0.75-m wavelength. With

[199] 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).

[200] For the efficiency figures see B.M. Starobin, "Loudspeaker Design," ch. 160 in Crocker (note 186). See also V. Salmon, "Horns," ch. 61 in Crocker (note 186), and literature cited there.

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.[201]

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 required 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%.[202] 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.[203]

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) that the National Center for Physical Acoustics at the University of Mississippi built for the Battlefield Environment Directorate of the U.S. Army Research Laboratory.[204] 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-trailer. 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 center of the horn opening), i.e., already in the immediate vicinity.[205] The 120 dB range is 40 m.

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[201] 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 (2) (October 1946), pp. 371-87.

[202] Allen and Rudnick (note 133); Allen et al. 1948 (note 133).

[203] Parrack 1952 (note 137).

[204] J. Sabatier, "Acoustical Characterization of the Mother of All Speakers" (University MS: National Center for Physical Acoustics, 26 May 1993); http://w3.arl.mil/tto/ARLDTT/FoxProdata/fac50.html.

[205] 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-10) occurs the decrease is not monotonical because of sidelobes). With a

For infrasound, the increasing pain threshold and decreasing horn efficiency combine to prevent ear pain even close to the mouth of the siren, 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.[206] 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.[207]

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.[208] 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. According to eqs. (A-14) to (A-24), however, shock would set in at about 0.1 m,

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slightly smaller horn of 2.1 m diameter, at 40 Hz (*ka*=0.8) the intensity was still essentially the same in all directions.

[206] 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 65); see also Gavreau 1968 (note 65).

[207] Yu. Ya. Borisov, "Acoustic Gas-Jet Generators of the Hartmann Type," part I in L.D. Rozenberg (ed.), *Sources of High-Intensity Ultrasound* (New York: Plenum Press, 1969); see also: Parrack 1952 (note 137); and H. Kuttruff, *Physik und Technik des Ultraschalls* (Stuttgart: Hirzel, 1988), pp. 140 ff.

[208] J.A. Gallego-Juarez, G. Rodriguez-Corral, and L. Gaete-Garreton, "An Ultrasonic Transducer for High Power Applications in Gases," *Ultrasonics* 16 (November 1978), pp. 267-71.

increasing the losses. 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.[209]

Finally, there is the possibility of producing a shock pulse by an *explosive blast*, as described in A.4 of the appendix. As shown in fig. A.2, 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. 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 that 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. As mentioned in A.4, strong-shock waves expanding into free air suffer from diffraction from the beginning, even though modified by the pressure dependence of speed. 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.

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[209] J.A. Gallego-Juarez and 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 (November 1979), pp. C8-336 to C8-340; the total level was estimated from the levels of the individual harmonics.

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, and potentially much higher values with micromechanical valves. Of course, cooling, withstanding the overpressure pulse, and the recoil will present formidable, but solvable, engineering problems. Let us ask what might be required to produce 1 MW of acoustic power.[210] Assuming that half the thermal energy released goes into the shock wave,[211] 2 MW=2 MJ/s of primary power have to be spent. With gasoline or Diesel fuel of about 44 MJ/kg specific energy content, 1 kg would suffice for 22 seconds of operation. Continuous operation for one full day would need 3.9 Mg, thus the statement by the SARA firm—for fixed installations tank storage for a month—seems credible.[212] For the 45 g fuel burnt per second, about 160 g oxygen would be needed, which is contained in about 0.55 m^3 of air.[213] (A tank engine running at 1 MW full mechanical power at 1/3 efficiency needs 1.5 times these values.) After the first shock, each subsequent 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. Due to the large volume of air affected at distances of a few tens of meters, air heating would remain insignificant except close to the source.[214] Assuming a circular source of 1 m diameter, the intensity would result to 1.3 MW/m^2 and the level to 181 dB, still marginally in the weak-shock region. With symmetric shocked waves, this would correspond to a sound pressure of about 22 kPa.[215] Quantitative estimates of the overpressure decrease with increasing distance

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[210] Megawatt power was mentioned by SARA (note 16).

[211] From an approximate treatment for much higher than atmospheric pressures one can derive that a 0.25 portion goes into the shock wave. At later stages of real explosions with lower overpressures, several times 10% (depending on specific-heat ratio γ) remain as thermal energy in the center, whereas the rest is transported with the shock wave and finally dissipated as well: Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, vol. I (New York and London: Academic Press, 1966), I §26, 27.

[212] SARA (note 16). Note that this assumes inhaling air as oxidizer. Were liquid explosive used, which contains the oxidizer already in the molecule, specific energy would be approximately 1/10, and required fuel supplies 10 times, the values given. With, e.g., 100 explosions per second, each of them would take about 5 g of TNT equivalent (TNT melts at 81°C). Of course such fuel would be much more dangerous.

[213] Estimated from $C_{10}H_{22}$ (142 g/mole), one mole of which needs 15.5 moles O_2 (32 g/mol), i.e., 496 g; oxygen mass fraction in air 0.23, air density 1.2 kg/m^3.

[214] Conservatively assuming that all acoustical energy of 1 MJ emitted per second remains within a conical sphere section of 45° full angle and 50 m radius (volume $2 \cdot 10^4$ m^3), with a specific heat capacity of 1.2 kJ/(kgK) one arrives at an average temperature rise of 0.03 K per second.

[215] For symmetric-wave propagation of such source level at 16 kHz see 5.1.2.

and angle from the axis require much more clarification by the developers of such systems and/or a detailed theoretical study.[216]

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.[217] Aerodynamic flaps, a parachute, or the like could stop the projectile at the target distance.

In conclusion, it is possible to construct strong sources of low-frequency sound which can be tuned to some extent, or that 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.

4. Protection from High-Intensity Sound, Therapy of Acoustic and Blast Trauma

4.1 Protection from 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-

[216] For treatments of slightly related problems see: Y. Inoue and T. Yano, "Propagation of Strongly Nonlinear Plane Waves," *Journal of the Acoustical Society of America* 94 (3, Pt. 1) (September 1993), pp. 1632-42; and Y. Inoue and T. Yano, "Strongly Nonlinear Waves and Streaming in the Near Field of a Circular Piston," *Journal of the Acoustical Society of America* 99 (6) (June 1996), pp. 3353-72.

[217] 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 38).

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.[218]

Protection against whole-body exposure can principally be provided by enclosures that are sufficiently stiff so that they are not easily vibrationally excited, thus transmitting sound to the inside, or by linings with sound-absorbing, e.g., porous material. For jet engine technicians, protective suits exist.[219] 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.[220] 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,[221] 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.

4.2 Therapy of Acoustic and Blast Trauma[222]

Here only a few indications will be given.[223] Some immediate effects of over-exposure 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.

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[218] C.W. Nixon and 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, and H.R. Beitscher, *Journal of the Acoustical Society of America* 28 (4) (July 1956), pp. 631-38.

[219] Jansen 1981 (note 131).

[220] R. Moulder, "Sound-Absorptive Materials," ch. 30 in Harris (note 48).

[221] 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.

[222] 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.

[223] There is, of course, a considerable body of medical literature on aural injuries and their treatment; see, e.g., Paparella et al. (note 51).

There are conflicting studies on the success of such treatment.[224] 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.[225]

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.[226] Fracture or displacement of middle-ear ossicles occurs more rarely and indicates much more severe blast damage; these require much more complicated surgery.[227]

Whereas there are cases when nearly full recovery of hearing has occurred even after ruptures of both eardrums, it is more likely that PTS—of moderate to severe extent—ensues.[228] 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.[229] Prevention, e.g., by ear protection, is the only reliable way to avoid permanent hearing losses.[230]

5. Analysis of Specific Allegations with Respect to Acoustic Weapons

The following subsections deal with a few allegations made mostly in journalistic articles. In 5.1, scientific and technical analyses concerning weapons principles are presented. Section 5.2 covers in brief a few aspects of the effects on humans.

5.1 Allegations Regarding Weapons Principles

5.1.1 Infrasound Beam from a Directed Source?

Several journalistic articles speak of an "infrasound beam" (see table 1). The detailed analysis is given in appendix A.5. It is clear from the beginning [see eq. (A-13)] that for long

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224 Ward 1991 (note 51). 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 (3) (1992), pp. 435-43.

225 Ward 1991 (note 51).

226 Chait et al. (note 166); J.D. Casler, R.H. Chait, and J.T. Zajtchuk, "Treatment of Blast Injury to the Ear," *Annals of Otology, Rhinology & Laryngology* 98 (5, pt. 2, Suppl. 140) (May 1989), pp. 13-16; and respective references.

227 See the references in Chait et al. (note 166).

228 See, e.g., Kerr and Byrne (note 166).

229 Papers of the International Cochlear Implant, Speech and Hearing Symposium, *Annals of Otology, Rhinology & Laryngology* 104 (9, pt. 2, Suppl. 166) (September 1995), pp. 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), pp. 28-33; M.J.A. Makhdoum, A.F.M. Snik, and P. van den Broek, "Cochlear Implantation: A Review of the Literature and the Nijmegen Results," *Journal of Laryngology and Otology* 111 (November 1997), pp. 1008-17; and papers of the third European Symposium on Pediatric Cochlear Implantation, *American Journal of Otology* 18 (6 Suppl.) (November 1997), pp. S1-S172.

230 Ward 1991 (note 51).

wavelengths a large emitting area will be needed to achieve substantial intensity at some distance. 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 source mentioned in 3.2).[231]

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, 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 have been observed at about 150 dB level (see 2.2.3.4), 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.

It is interesting to analyze what happens at higher frequencies, where shorter wavelengths facilitate focused propagation. Estimates from 500 Hz to 10 kHz are given in appendix A.5. The main result is that 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.

5.1.2 Infrasound from Non-Linear Superposition of Two Directed Ultrasound Beams

One of the alleged early acoustic weapons (the "squawk box" mentioned in 1.2) was said to utilize two near-ultrasound waves that would combine in the ear, producing an intolerable infrasound difference frequency (together with the ultrasound sum frequency).[232] 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.[233] 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

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[231] See note 205.

[232] "Army tests" (note 18).

[233] Liszka (note 40).

vestibular system (see 2.2.3.2). Non-linear production of difference-frequency signals can occur either during propagation in the air or within the ear. Both are treated in appendix A.6.

First to conversion in the air: as discussed with eq. (A-34), 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 at 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 (see 3.2). 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. Realistically, an intensity on the order of 1 MW/m^2 at the source may be possible eventually [180 dB, bordering on weak shock where eq. (A-34) holds];[234] 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 (appendix A.6). 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;[235] 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 center 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.

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[234] See also blast sources in section 3.2.

[235] J.J. Guinan, Jr. and W.T. Peake, "Middle-Ear Characteristics of Anesthetized Cats," *Journal of the Acoustical Society of America* 41 (5) (1967), pp. 1237-61. 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.

This is about a factor of 10 or 20 dB above the capabilities of the strongest periodic ultrasound sources available (see 3.2). 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 occur until the third, amplitude-invariant stage starts at 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 2.4.2). Taking into account the conservative assumptions made, it therefore seems 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")[236] seems possible, on the other hand, since levels of a few tens of dB are sufficient for hearing.

5.1.3 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 United States, antennas of 1-2 m size have been mentioned; in Russia, the bullets were said to be basketball sized, with a frequency of 10 Hz, and to be selectable from non-lethal to lethal over hundreds of meters (see table 1).[237]

It is not clear what might be behind these reports. As shown in the appendix, 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 in 5.1.1. 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 (see 5.1.1), 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, in principle, a possibility of emitting different pulsed waveforms that 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 is 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," or 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

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[236] M.T. (note 5).

[237] Tapscott and Atwal (note 23); Starr (note 9); "Army Prepares" (note 25); M.T. (note 5).

ultrasound experiments over tens of centimeters in water have demonstrated at least some increase of the on-axis intensity, over the intensity from uniform continuous-wave excitation of the source array.[238] 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 [see eq. (A-17)] 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 described in appendix A.2, unusual dissipative losses occur in the shock front, 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,non-linear absorption destroys the effect at higher amplitude.

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 A.2) 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.[239] 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 relative to the source size, resulting in reduced amplitude.[240]

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

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[238] 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 (4) (15 February 1989), pp. 2005-33, and references cited therein; and Gang Wang and Wen Bing Wang, "Beam Characteristics of Short-pulse Radiation with Electromagnetic Missile Effect," *Journal of Applied Physics* 83 (10) (15 May 1998), pp. 5040-44. 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 (4) (April 1998), pp. 1742-51. For the ultrasound experiment see R.W. Ziolkowski and D.K. Lewis, "Verification of the Localized-wave Transmission Effect," *Journal of Applied Physics* 68 (12) (15 December 1990), pp. 6083-86.

[239] E.g.: E. Infeld and G. Rowlands, *Nonlinear Waves, Solitons and Chaos* (Cambridge: Cambridge University Press, 1990); and M. Remoissenet, *Waves Called Solitons—Concepts and Experiments* (Berlin: Springer, 1994).

[240] For a discussion of non-amplitude-preserving collapsing or expanding "solitons" in two- or three-dimensional plasma and other media, see Infeld and Rowlands (note 239), ch. 9.

slow. Finally, the ring breaks up into general turbulence.[241] Assessing the production, propagation, and effects of vortex rings could not be done here for time and space reasons. A few preliminary indications shall nevertheless be given. Vortex rings in air can propagate to more than about 100 times the orifice diameter;[242] vortex rings have been discussed as a means of extinguishing gas and oil well fires or of transporting pollutants to high atmospheric altitudes.[243] Thus, propagation from a 1–meter orifice to more than 100 m in undisturbed air is plausible. Assuming that at the target a ring of 1 m diameter (more than twice basketball size) would arrive with a uniform core of 0.2 m diameter and 100 m/s outer air speed, the ring speed would be 17 m/s.[244] According to eq. (3), the dynamic pressure for normal incidence would be 6 kPa (peak level 170 dB), as in the strongest sonic booms cited in 2.2.3. The time for core passage at one position would be about 12 ms, corresponding to 80 Hz. This would be faster than the sonic booms, and would affect only those parts of the body actually hit by the ring. Higher air speed would increase the pressure by its square, so that at high supersonic speeds even lung-damaging pressures (of 300 kPa, see 2.5.2) are conceivable. The latter would mean production by a shock, e.g., from an explosion in a tube, and such air speeds in the ring would probably only hold at close distance;[245] lethal effects at hundreds of meters seem very implausible. To what distances lower, but still relevant speeds could be achieved, cannot be clarified here. If the purpose of the ring were not to exert pressure, but only to transport some material (hot gas, irritants, or the like), the 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. Vortex rings are another area where an in-depth study is required; it will have to include potential sources,

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[241] For vortex-ring dynamics, see: H. Lamb, *Hydrodynamics*, 6th ed. (Cambridge: Cambridge University Press, 1932), ch. VII; P.G. Saffman, *Vortex Dynamics* (Cambridge: Cambridge University Press, 1992), ch. 10; K. Shariff and A. Leonard, "Vortex Rings," *Annual Review of Fluid Mechanics* 24 (1992), pp. 235-79; 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 (1), 15-32 (1972); T. Maxworthy, "Turbulent Vortex Rings," Journal of Fluid Mechanics 64 (2), pp. 227-39 (1974); and T. Maxworthy, "Some Experimental Studies of Vortex Rings," *Journal of Fluid Mechanics* 81 (3), pp. 465-95 (1977). For some information on U.S. efforts at vortex-ring weapons, see: G. Lucey and L. Jasper, "Vortex Ring Generators," in *Non-Lethal Defense III* (note 2); and J. Dering, " High Energy Toroidal Vortex for Overlapping Civilian Law Enforcement and Military Police Operations," ibid.

[242] Empirical laws on size and time of flight of turbulent vortex rings held at least to about 70 times the orifice diameter: G.M. Johnson, "An Empirical Model of the Motion of Turbulent Vortex Rings," *AIAA Journal* 9 (4) (1971), pp. 763-64.

[243] D.G. Akhmetov, "Extinguishing Gas and Oil Well Fires by Means of Vortex Rings," *Combustion, Explosions, Shock Waves* 16 (1980), pp. 490-94, cited after Shariff and Leonard (note 241); J.S. Turner, "On the Intermittent Release of Smoke from Chimneys," *Mechanical Engineering Science* 2 (1960), pp. 356 ff., cited after Maxworthy 1974 (note 241); Maxworthy 1974 (note 241).

[244] In a uniform ring the core rotates with a constant angular velocity ω_0, as if solid; with core radius a, the circulation is $\Gamma=\pi a^2\omega_0$. With 100 m/s outer speed and a=0.1 m, ω_0=1000 rad/s and Γ=31 m^2/s. With ring radius R, the ring speed is $U=\Gamma[\ln(8R/a) - 1/4)]/(4\pi R)$, resulting in U=17 m/s for R=0.5 m. Equations from, e.g., Saffman (note 241).

[245] For supersonic vortex rings in front of a shock tube see, e.g., M. Brouillette and C. Hebert, "Propagation and Interaction of Shock-generated Vortices," *Fluid Dynamics Research* 21 (3) (1997), pp. 159-69.

laminar and turbulent rings of sub- and supersonic gas speeds, and effects on the ears and other parts of the body, and will probably have to rely on numerical models. Additional complications by wind and topography could be analyzed later.

It may also be that journalists or observers have misunderstood something. For example, a focused beam of invisible laser light might produce a plasma in front of a target emitting a shock wave (see 5.1.4)—the propagation to the focus would, however, 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).

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

In the defense press, the small arms program liaison of the U.S. Joint Services Small Arms Program has been 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."[246] As shown in appendix A.7, plasma creation would require overpressures of many megapascals, as occur in the immediate vicinity of an exploding charge [and where—due to the temperature of several 1000 K—the air not only emits visible light, but is partially ionized; see eq. (A-36) and fig. A.2].

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 certainly be 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 center of a spherical shock tube,[247] projection to a distance much larger than the source, while avoiding spherical expansion with $1/r^3$ shock pressure decrease, seems unachievable (see 5.1.3 and A.4).

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 materiel and personnel."[248] In that case, the task of focusing over considerable distance would be alleviated by the short wavelength (on the order of μm) 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—this has been discussed in 2.5. Only the drag of the moving air behind the shock

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[246] Tapscott and Atwal (note 23), p. 45.

[247] See, e.g., I.I. Glass and J.P. Sislian, *Nonstationary Flows and Shock Waves* (Oxford: Clarendon, 1994), ch. 12.

[248] Tapscott and Atwal (note 23), p. 46.

front would exert a net force. Appendix A.7 shows that for a conventional explosion a shock overpressure of about 100 kPa would be required, as occurs with 1 kg TNT spherically exploding at only about 3 m distance. 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. Here again the same confusion with the laser-generated plasma has probably occurred. The case of a vortex ring—acting only on parts of the body—needs a separate analysis; see 5.1.3.

5.1.5 Localized Earthquakes Produced by Infrasound

An overview on non-lethal weapons has stated (without giving an explicit source) that acoustic weapons could affect buildings, not only by shattering windows, but even by "localized earthquakes."[249] One might define an earthquake by a soil motion sufficient to endanger buildings, which occurs at a soil speed markedly above 10 mm/s.[250] Taking this as a conservative limit and using a maximum acoustic-seismic transfer factor of 10^{-5} m/(Pas),[251] a low-frequency sound pressure of 1 Pa (level 154 dB) is required to achieve that soil speed. As demonstrated in 5.1.1, such levels are possible only in the immediate vicinity of a low-frequency source and 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 4.1). 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,[252] 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

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[249] Lewer and Schofield (note 2), p. 12.

[250] 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 and D.R. Leonard, "A Survey of Traffic-induced Vibrations," *RRL Report LR* 418 (Crowthorne, Berkshire: Road Research Laboratory, 1971), p. 14, table 4.

[251] With grassy soil this maximum value occurs typically around several times ten Hz; at different frequencies, it may be 5 to 10-fold lower. See: J.M. Sabatier et al., "Acoustically Induced Seismic Waves," *Journal of the Acoustical Society of America* 80 (2) (1986), pp. 646-49; and Altmann and Blumrich (note 192); 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).

[252] "Non-lethal Devices Slice Across Science Spectrum," *National Defense* (October 1993), p. 25, quoted after Arkin (note 16).

coupling from the source.[253] The same would hold for embrittlement or fatigue of metals, delimitation of composite materials, etc.[254]

5.2 Allegations Regarding Effects on Persons

There are a few allegations concerning high-power sound effects on humans that make a strong impression when being read, but are difficult to confirm from the scientific literature. This concerns mainly vomiting and uncontrolled defecation.[255] 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).[256] In close vicinity to jet engines, in a systematic study unsteadiness and imbalance were observed, but nausea occurred only in some employees some time 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.[257] 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 mention of even nausea,[258] 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.[259] With animals tested at low frequencies with up to 172 dB, vomiting was not mentioned at all.[260]

Evidence for bowel spasms and uncontrolled defecation is even scarcer. Among all the literature surveyed for this report, 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.[261] In the low-

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[253] Note that modern industrial buildings without plaster can stand earthquakes with soil vibrations of 20-40 mm/s: Whiffin and Leonard (note 250).

[254] Lewer and Schofield (note 2), p. 12.

[255] Vomiting: "Non-lethality" (note 2); Evancoe (note 22); Kiernan (note 20); Morehouse (note 2). Uncontrolled defecation or diarrhea: Kiernan (note 20); Toffler and Toffler (note 16), p. 187; bowel spasms: "Non-lethality" (note 2), Morehouse (note 2).

[256] High audio frequencies: Allen et al. 1948 (note 133); ultrasound: Parrack 1952 (note 137); Parrack 1966 (note 110); Acton and Carson (note 137). See also note 137.

[257] Dickson and Chadwick (note 124).

[258] Parrack 1966 (note 110).

[259] Mohr et al. (note 77).

[260] E.g., with whole-body-exposed awake guinea pigs and monkeys: Parker, in Tempest (note 66).

[261] Gavreau et al. 1966 (note 65), p. 9.

frequency exposures up to 150 dB no bowel spasms were observed.[262] The same holds for low-frequency animal experiments.[263] Here it is noteworthy that also in reviewing vibration experiments no mention was made of bowel spasms or uncontrolled defecation.[264]

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.[265] 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.[266] Similarly, there are no indications for the alleged low-frequency-produced internal hemorrhages.[267] For *vibration*-induced gastrointestinal hemorrhages, on the other hand, see 2.2.4.

Thus, it seems that these alleged effects are based more 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.

6. 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 to the ear, and in the extreme even to 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 report aims at providing facts that can 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.

6.1 Effects on Humans

Contrary to several articles in the defense 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 evi-

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[262] Mohr et al. (note 77). Note that testicular aching (a different potentially embarrassing effect) of one subject was reported here.

[263] See note 260.

[264] Section 5.3 in Griffin (note 64).

[265] Lumsden (note 15), p. 203.

[266] Mohr et al. (note 77).

[267] SARA (note 16).

dence 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, even short exposures at levels above, say, 135 dB can produce lasting damage to 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 of hair may become important above about 160 dB.

Early therapy may lead to some improvement after acoustic trauma. However, permanent hearing loss, once it has 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.

6.2 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.

6.3 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 insurmountable 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 sawtooth 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 waves form earlier and the associated energy losses become stronger with increasing frequency; thus, even if for some high enough frequency diffraction did not significantly reduce the sound pressure at a distance, shock-wave losses would 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, and 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 the human tolerance is higher for impulses, 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 lethal even 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.

6.4 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.

6.5 General Remarks

With acoustic weapons, as with other types of "non-lethal" 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 that 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.[268]
- 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

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[268] 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), p. 336; "Blinding laser weapons . . ." (note 6), pp. 28 ff.

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 bystanders 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."[269] 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 respect 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 of applications were limited to the law of warfare proper.

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[269] 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.

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 report contributes to that debate.

Appendices

Appendices A.1 to A.4 deal with basic properties of pressure waves in air. A.5 to A.7 analyze allegations concerning acoustic weapons effects.

A.1 Linear Acoustics[270]

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.

In order to estimate the sound pressure of a simple source one can use the assumption of a monopole (i.e., a breathing sphere) emitting spherical waves in the open or in an anechoic chamber. In this case, the sound pressure p—i.e., the deviation from the static pressure P_0 at distance r from the center at time t in the far field—depends on the volume flow $Q(\tau)$ at the source:

$$p(r,t) = \rho_0\, Q'(t - r / c_0) / (4\pi\, r) \qquad \text{(A-1)}$$

independent of direction, where ρ_0 is the air density, and the time derivative $Q'(\tau)$ of the volume flow is taken at the retarded time, when the signal had left the source. The volume flow is the integral over the gas flow speed over the source (here: sphere) area. For a periodic source vibrating with frequency ν with the volume flow

$$Q(\tau) = A\, v_0 \sin \omega\, \tau \qquad \text{(A-2)}$$

($A = 4\pi a^2$ is the surface, a the radius, v_0 the velocity amplitude, $\omega=2\pi\nu$ the angular frequency) one gets

$$p(r,t) = \rho_0\, c_0\, k\, 4\pi\, a^2\, v_0\, \cos(\omega t - kr) / (4\pi\, r) \qquad \text{(A-3)}$$

($k=2\pi/\lambda$ is the wavenumber, $\lambda=c_0/\nu$ the wavelength), and the root-mean-square (rms) pressure becomes

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

where v_{rms} is the rms surface velocity of the sinusoidal vibration.

The product $Z_0=\rho_0 c_0$ is the impedance of free air, it links momentary pressure with momentary longitudinal gas particle speed v anywhere in the far-field wave for general wave forms,

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

$$p(r,t) = \rho_0\, c_0\, \mathrm{v}(r,t) \qquad \text{(A-5)}$$

(the near-field contribution out of phase vanishes faster with *r*).

The rms intensity, i.e., the rms power per area transported with the wave, is

$$I_{rms}(r) = p_{rms}^2(r) / (\rho_0\, c_0); \qquad \text{(A-6)}$$

it decreases with $1/r^2$ since the rms pressure decreases with $1/r$. (Of course, for sinusoidal wave the rms value is $2^{-1/2}$ of the amplitude.) The total power P_{rms} emitted is the integral over the full sphere at *r*,

$$P_{rms} = 4\pi r^2 I_{rms}(r), \qquad \text{(A-7)}$$

which is constant absent other losses.

From (A-6) and (A-7), the root-mean-square sound pressure and total acoustic power of the source are linked by

$$p_{rms}(r) = (\rho_0\, c_0 P_{rms} / 4\pi)^{1/2} / r\,. \qquad \text{(A-8)}$$

Additional attenuation of sound pressure takes place by absorption, caused on the one hand by classical processes (bulk and shear viscosity, thermal conductivity), on the other by molecular excitation. It can be described by an exponential decay where for a plane wave propagating in *x* direction the pressure decreases from p_{rms0} at x=0 to

$$p_{rms}(x) = p_{rms0} \exp(-\alpha\, x) \qquad \text{(A-9)}$$

at distance *x*. For a spherical wave, the $1/r$ dependence by geometrical attenuation has to be multiplied in addition. Generally the absorption coefficient α increases with the square of the frequency; however, modifications arise as the contributions of individual molecular relaxation processes become constant at certain frequencies.[271] In particular the relative humidity of air has a strong influence, since the presence of three-atomic molecules facilitates vibrational relaxation of N_2 and O_2 molecules. This leads to marked variations of the frequency dependence of α. Typical values for the range from 10 to 90% relative humidity are: at 125 Hz, $(9 \text{ to } 3)\cdot 10^{-5}\ \mathrm{m}^{-1}$; at 1 kHz, $(1.6 \text{ to } 0.6)\cdot 10^{-3}\ \mathrm{m}^{-1}$; at 20 kHz, $(0.03 \text{ to } 0.05)\ \mathrm{m}^{-1}$.[272] These figures mean that low-frequency

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[271] J.E. Piercy, T.F.W. Embleton, and L.C. Sutherland, "Review of Noise Propagation in the Atmosphere," *Journal of the Acoustical Society of America* 61 (6) (June 1977), pp. 1403-18.

[272] Piercy et al. (note 271); J.E. Piercy and G.A. Daigle, "Sound Propagation in the Open Air," ch. 3 in C.M. Harris (ed.), *Handbook of Acoustical Measurements and Noise Control* (New York: McGraw-Hill, 1991); Pierce (note 270), section 10-7. Note that the humidity dependence is not always monotonical.

sound is practically not affected, whereas ultrasound at 20 kHz is attenuated to a few per cent after passing 100 m.[273]

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 4π/Ω, 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

$$p_{rms}(r,\vartheta) = \frac{\rho_0\, c_0}{4\pi r} k\, 2 v_{rms} \pi a^2 \, \frac{2 J_1(ka \sin\vartheta)}{ka \sin\vartheta} \qquad \text{(A-10)}$$

again $k=2\pi/\lambda$ is the wavenumber, and $\lambda=c_0/\nu$ the wavelength. The Bessel function expression $2\,J_1(x)/x$ is close to 1 from $x=0$ to about π/2. Comparison with (A-4) 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,[274] 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.[275] When the wavelength λ is longer than 2π*a*, the circumference of the piston, the argument of the Bessel function term is below π/2 even for ϑ=π/2, the second fraction in (A-10) 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 ν=50 Hz (λ=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.[276] 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%.[277]

As long as propagation is linear, all wave phenomena observed with other (e.g., electromagnetic) linear waves apply also for sound waves. There is the Huygens principle of elementary wavelets the superposition of which gives diffraction effects. If parallel waves of constant intensity are emitted by a circular antenna (lens, mirror, array of small sources), 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-10):

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[273] Note that for intensity which is proportional to squared pressure the attenuation coefficients have to be doubled.

[274] 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.

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

[276] See, e.g., V. Salmon, "Horns," pp. 1925-31 in Crocker (note 186), and literature cited there.

[277] B.M. Starobin, "Loudspeaker Design," ch. 160 in Crocker (note 186).

$$\sin \varphi_1 = 1.22\ \lambda / D \qquad \text{(A-11)}$$

where λ is the wavelength and *D* is the diameter of the antenna. If the expression on the right is larger than 1, there is no null at all. The angle is the same if the source does not emit parallel wave fronts, but spherical ones, e.g., converging—as in optics—in the focal plane of a mirror or lens. In a distance *r* the radius a_1 of the inner diffraction spot is

$$a_1 = r \tan \varphi_1 \qquad \text{(A-12)}$$

for the spot in a focal plane the focal length has to be used for *r*. For small φ_1, sine and tangent can be neglected in (A-11) and (A-12). The principal limitation of the spot size to be no smaller than λ/2 is seldom relevant with sound.

The intensity on the axis can be derived from (A-10) with ϑ=0, assuming that the piston is replaced by a hole on which a plane wave impinges from the back, producing the same air velocity. In this case the pressure can be computed with the impedance of free air from (A-5).[278] Finally, with (A-6) for the intensity and the power *P* emitted from the hole as the integral over the area, one obtains

$$I_{\max}(r) = P\pi D^2 / (4\lambda^2 r^2) \qquad \text{(A-13)}$$

In the case of outdoor sound propagation, modifications apply due to several effects.[279] For source and receiver above ground, reflection leads to frequency-dependent increases and decreases; often due to pores the ground is not acoustically hard so that the phases of the reflected waves vary with frequency and incidence angle. Temperature layers or wind shear refracts waves upward for a normal temperature gradient or up-wind propagation, or downward for an inversion or down-wind propagation. Hills and valleys, woods or buildings make wave fields more complicated. Finally, waves are scattered at turbulent refractive-index modulations which can reduce the shadowing effect of an upward-refracting atmosphere. Most of these effects are small for the distances (10 to 100 m) considered here; since they are variable and calculations are complicated, for the simple estimates of the present assessment they will be neglected. However, some of these effects, e.g., refraction, 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.

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[278] In case of a solid piston the near field is more complicated, and the impedance is a frequency-dependent complex quantity; see Morse and Ingard (note 270), pp. 383 ff.

[279] Piercy et al. (note 271); T.F.W. Embleton, "Tutorial on Sound Propagation Outdoors," *Journal of the Acoustical Society of America* 100 (1) (July 1996), pp. 31-48.

A.2 Non-Linear Acoustics—Weak-Shock Regime[280]

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 (fig. 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 (fig. A.1 b). This can also be described as the successive build-up of harmonics of the original frequency (for an ideal sawtooth 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 (fig. A.1 c). The details are complicated; in the following, only the most important characteristics will be described.

In weak shock, the acoustic Mach number

$$M = v_0 / c_0 \qquad \text{(A-14)}$$

(v_0: particle velocity amplitude, c_0: small-signal sound speed) is much smaller than unity. The acoustic Reynolds number

$$Re = v_0\, c_0\, \rho_0 / (b\omega) = p_o / (b\omega) \qquad \text{(A-15)}$$

(p_0: pressure amplitude, ρ_0: density at rest, $\omega=2\pi\nu$ angular frequency) is a measure of the relative importance of the non-linear versus the dissipative processes. In the classical case, the coefficient *b* contains the coefficients of bulk and shear viscosity ζ and η as well as of thermal conductivity κ:

$$b = \zeta + 4\eta / 3 + \kappa(c_v^{-1} - c_p^{-1}) \qquad \text{(A-16)}$$

(c_v and c_p are the specific heats at constant volume and pressure, respectively) and the absorption coefficient becomes

$$\alpha = b\omega^2 / (2 c_0^3 \rho_0) \qquad \text{(A-17)}$$

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[280] See, e.g., O.V. Rudenko and S.I. Soluyan, *Theoretical Foundations of Nonlinear Acoustics* (New York and London: Consultants Bureau, 1977). Note that for consistency with the rest of the paper I have changed the description from particle velocity v to pressure *p* using $p=c_0\rho_0 v$, which is valid as long as these quantities are small against *P*, ρ_0 (i.e., $M << 1$), which is the case for weak shock. See also: G.B. Whitham, "Linear and Nonlinear Waves" (New York: Wiley, 1974); and S. Makarov and M. Ochmann, "Nonlinear and Thermoviscous Phenomena in Acoustics, Part II," *ACUSTICA—Acta Acustica* 83 (2) (March/April 1996), pp. 197-222. Note that there are additional effects such as sonic wind which, however, are less relevant here.

where the quadratic dependence on frequency is obvious. Molecular relaxation can be included by using an empirical, larger coefficient *b*. For air in the low audio region (0 to several 100 Hz) $b=6\cdot10^{-3}$ kg/(sm) can be used, from a few kHz to a few tens of kHz $3\cdot10^{-4}$ kg/(sm) is appropriate; but the variations by factors two and more due to humidity have to be kept in mind.[281] With the dissipative losses, changes in the medium are no longer adiabatic; losses are strongest in the shock front.

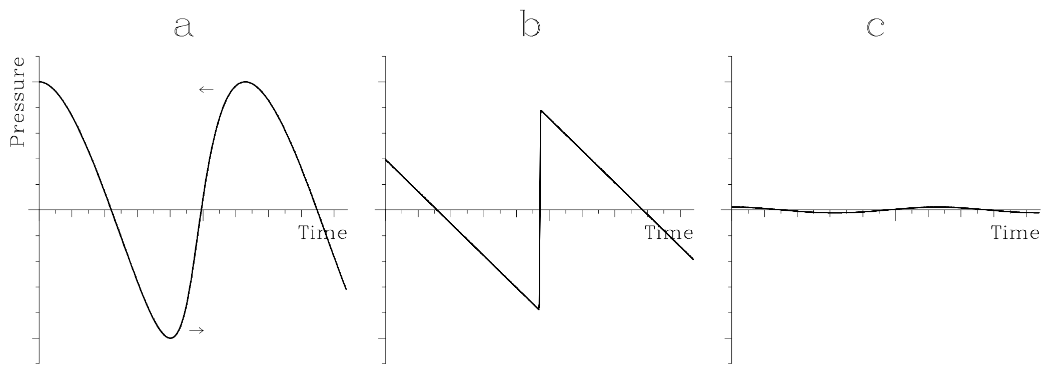

Fig. A.1 Wave forms of an originally harmonic wave before and after shock formation. In the first stage (a), pressure peaks move faster and troughs more slowly, deforming the wave as it propagates. In the second stage, a rounded sawtooth wave forms with strong dissipation in the shock front (b). The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

The basic processes can be explained in second-order approximation by starting with a plane sinusoidal wave of pressure and velocity amplitudes p_0, v_0 at x=0. According to the respective pressures, peaks propagate slightly faster and troughs slightly more slowly, deforming the wave along its path. If non-linear processes dominate over dissipative ones (*Re* >> 1), a shock front develops where one part of the wave would start to overtake another one, at distance

$$x_p = \lambda / (\pi(\gamma+1)M) \qquad \text{(A-18)}$$

The specific-heat ratio is $\gamma=c_p/c_v=1.4$ for diatomic gases such as air. The longer the wavelength, the farther peaks and troughs have to move before overtaking would take place. Up to this distance x_p the amplitude stays approximately the same. With M=0.01, i.e., v_0=3.4 m/s, $p_0=0.014\cdot P_0$=1.4 kPa, level 154 dB, the distance to the shock is only 13 wavelengths—45 m at 100 Hz, 45 cm at 10 kHz. From here on the wave propagates as a shocked one with a rounded sawtooth shape (second stage, fig. A.1 b). The thickness of the front is

[281] Derived from fig. 3 in Piercy et al. (note 271); for the variation with humidity see fig. 1 in Piercy et al. (note 271), Table 3.1 in Piercy and Daigle (note 272) and eq. 10-7.24 in Pierce (note 270).

$$d = \delta \lambda / (2\pi) \qquad \text{(A-19)}$$

with the dimensionless thickness parameter

$$\delta = (1 + x / x_p) / (\pi \, Re \, (\gamma + 1) / 2) \qquad \text{(A-20)}$$

The wave moves with the small-signal sound speed c_0. With M=0.01 at 100 Hz and $b=6 \cdot 10^{-3}$ kg/(sm) the Reynolds number (A-15) is Re=371 and the starting thickness at $x=x_p$ becomes d=0.77 mm, less than 1/2000 of a half wavelength; at 10 kHz with $b=3 \cdot 10^{-4}$ kg/(sm), Re=45 and the starting thickness d=39 µm (less than 1/400 of λ/2). In a coordinate system moving together with the zero crossing ($\tau=t-x/c_0$), the wave form is described by

$$p(x, \tau) = (-\omega\tau + \pi \tanh(\omega\tau / \delta)) \;\; p_0 / (1 + x / x_p) \qquad (-\pi \le \omega\tau \le \pi) \qquad \text{(A-21)}$$

The front starts out thin, and its thickness increases with x. This is equivalent to a reduction of the higher harmonics. At the same time, the amplitude decreases. When the thickness has grown to about half a wavelength ($\delta \approx \pi$), there is no longer a shock front, and the wave is approximately sinusoidal again. This occurs at distance

$$x_0 = 2 / \alpha = 4 Re \; c_0 / (M \omega) = 4 \rho_0 c_0^{\,3} / (b \omega^2) \qquad \text{(A-22)}$$

In the example with M=0.01 and 100 Hz, x_0 becomes 82 km—a wave remaining plane over such distance is of course unrealistic if only because of diffraction—with 10 kHz, x_0=164 m), from here on the wave propagates as a linear damped harmonic wave according to

$$p(x, \tau) = 4 p_0 / ((\gamma + 1) Re) \;\; \exp(-\alpha \, x) \;\; \sin \omega\tau \qquad \text{(A-23)}$$

The amplitude of this third-stage wave

$$4 p_0 / ((\gamma + 1) Re) \quad \exp(-\alpha \, x) = 4 b \omega / ((\gamma + 1) \rho_0 c_0) \quad \exp(-\alpha \, x) \qquad \text{(A-24)}$$

is independent of the original amplitude p_0. In the example with 100 Hz, α becomes $2.4 \cdot 10^{-5}$ m^{-1} due to (A-17), and the (fictitious) amplitude at x_0 is 2.1 mPa (37 dB re. 20 µPa rms); with 10 kHz, α=0.012 m^{-1}, and the exponential decrease starts with amplitude 10 mPa (51 dB).) The reason for this saturation is that if a shock develops at all, increases in starting amplitude p_0 lead to an earlier inset of shock, with a thinner front, and correspondingly higher losses until the end of the second phase.[282]

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[282] For an experimental confirmation see D.A. Webster and D.T. Blackstock, "Finite-amplitude saturation of Plane Sound Waves in Air," *Journal of the Acoustical Society of America* 62 (1977), pp. 518-23. Note that this experiment was done in a tube and that the authors incorporated absorption in a different way into their theoretical considerations.

In summary, the rms sound pressure of a plane wave stays essentially constant during the first phase. After shock formation it decreases approximately as $1/x$ to a low saturation value which is reached at twice the inverse absorption coefficient—note that this decrease is not due to geometrical spreading. Then final attenuation is exponential.

In case of other, non-sinusoidal signal forms, the distances to shock formation, the shock front thickness, etc. are different, but the basic processes are the same. In case of asymmetric waves, the propagation speed is about the mean of the speeds of the pressure minimum and maximum. If pulses of different amplitudes are superposed, a stronger one can overtake a weaker one and both will merge. In third-order approximation, the positive part of the sawtooth wave lasts longer than the negative one, and a positive mean pressure develops.[283]

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. The growth occurs logarithmically with the radius. Assuming a spherical wave starting at radius r_0 with pressure amplitude p_0, in the shocked stage the pressure is approximately given by [compare (A-21)]

$$p(r,\tau) = (-\omega\tau + \pi \tanh(\omega\tau/\delta)) \;\; p_0 r_0 / (r(1 + Z_0 |\ln(r/r_0)|) \qquad \text{(A-25)}$$

where the dimensionless thickness [see (A-19)] is

$$\delta = (1 + Z_0 |\ln(r/r_0)|)\, r / (\pi\, Re\; r_0) \qquad \text{(A-26)}$$

and the constant

$$Z_0 = (\gamma + 1)\omega\; p_0 r_0 / (2\rho_0 c_0{}^3) \qquad \text{(A-27)}$$

is the value of a dimensionless logarithmic radius coordinate

$$Z_1 = Z_0 |\ln(r/r_0)| \qquad \text{(A-28)}$$

at the radius where r/r_0=e. A shock discontinuity develops where Z_1=1, i.e., at radius

$$r_p = r_0 \exp(1/Z_0) \qquad \text{(A-29)}$$

For diverging waves and small Z_0 there will be no shock at realistic distances. If a shock develops at all, it ceases to exist beyond

$$r_{\lim} = r_0 \exp(Z_{\lim}) \qquad \text{where} \qquad Z_{\lim} = Z_0{}^2\, Re \qquad \text{(A-30)}$$

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[283] Makarov and Ochmann (note 280); see also Y. Inoue and T. Yano, "Propagation of Strongly Nonlinear Plane Waves," *Journal of the Acoustical Society of America* 94 (3, Pt. 1) (September 1993), pp. 1632-42.

In case of bounded waves (beams), diffraction has to be included into the considerations. The relative contribution of non-linear versus diffraction effects are described by a number

$$N = (\lambda / a)^2 / (\pi^2 (\gamma + 1) M) = x_p / x_{div} \qquad \text{(A-31)}$$

x_{div} is the distance needed to transform a plane wave to a spherically diverging one, *a* is the starting beam radius. Large values of *N* mean that diffraction dominates and propagation can be treated as linear, with all the usual effects of diffraction. If *N* is much smaller than unity, on the other hand, non-linear effects are most important. In this case, starting with a bounded wave of plane wave fronts, shock is first formed on the axis, since the amplitude is strongest there. Thus, dissipation is strongest on the axis as well, the beam profile becomes flatter, and the beam half-width increases. If the propagation can no longer be described in one dimension, the positive sawtooth peaks remain sharp whereas the negative troughs become rounded.[284]

For unipolar pulses starting as plane bounded beams, in case of overpressure the center moves faster which leads to additional divergence. In parallel, the pulse contracts in time. Conversely, a rarefaction pulse during propagation is narrowed in space and prolonged in time.

Finally, it needs to be mentioned that in case of a converging spherical pulse the non-linearity accelerates the convergence. Here as well as in the other cases above, more concrete answers require detailed studies.[285]

A.3 Non-Linear Acoustics—Production of Difference Frequency, Demodulation[286]

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. Since there is practically no dispersion in air, constructive interference of the difference-frequency contributions produced at several locations with speed-of-sound delays requires that the original waves propagate in the same direction; then the difference wave will have the same direction, too.[287]

Another advantage is that the sources are distributed along a line (end-fire array) so that constructive interference in the far field exists only in a small angular region around the axis.

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[284] Makarov and Ochmann (note 280).

[285] 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 and S. Tjøtta, "Nonlinear Equations of Acoustics," in M.F. Hamilton and D.T. Blackstock (eds.), *Frontiers of Nonlinear Acoustics: Proceedings of 12th ISNA* (London: Elsevier, 1990), pp. 80-97. For on-going research, see the series of International Symposia on Non-linear Acoustics.

[286] See, e.g., Rudenko and Soluyan (note 280).

[287] This is different from, e.g., optical mixing in a non-linear crystal where phase-matching of all three waves of different frequencies works only in certain directions. That there is no dispersion in air is also the reason why there are no solitary waves (solitons).

Thus the beam width is much smaller than if a source of the same size had emitted the low-frequency signal immediately with the accompanying strong diffraction widening due to the long wavelength.[288]

In concrete terms, superposition of two waves of similar frequency at first produces a variation in amplitude with the frequency difference. An amplitude-modulated wave, starting with

$$p(\tau) = p_0\,(1 + m\sin\Omega t)\sin\omega\tau \qquad \text{(A-32)}$$

($m \leq 1$ is the degree of modulation) is conceptually similar, and it can of course be produced by superposition of monochromatic side-band waves. In case of plane waves, the modulation- or difference-frequency-wave amplitude at first increases linearly with distance, in proportion to the squared original amplitude respectively the product of the individual amplitudes. If the non-linearity is dominant (*Re* >> 1), the wave will deform to shocked state at distance

$$L = 2c_0^{\;3}\rho_0 \,/\, ((\gamma+1)\,\omega\, p_0) \qquad \text{(A-33)}$$

for difference-frequency generation, replace p_0 by $(p_{01}p_{02})^{1/2}$ where p_{01}, p_{02} are the starting amplitudes of the two original waves. The linear amplitude increase with distance will at first continue, but will then—in the absence of absorption—saturate to a constant, with linear dependence on original amplitude

$$p_\Omega = \pi\, m\Omega\; p_0 \,/\, (4\omega) \qquad \text{(A-34)}$$

This holds for a triangular wave and is correct except a constant factor for an originally sinusoidal one too, analogously for the difference frequency.[289] It has to be noted that the dependence of the difference-frequency amplitude on the squared original amplitude as derived by several authors holds only in the case of no shock, respectively in front of the shocked region.[290] Including absorption, which increases with the square of the frequency, it may occur that the original wave(s) decay to lower amplitude than the respective modulation- (difference-) frequency wave at some distance. However, (A-34) means that the sound pressure of the low-

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[288] For a theoretical treatment (without shock) see P.J. Westervelt, "Parametric Acoustic Array," *Journal of the Acoustical Society of America* 35 (4) (April 1963), pp. 535-37. For experiments in air, see M.B. Bennett and D.T. Blackstock, "Parametric array in air," *Journal of the Acoustical Society of America* 57 (3) (March 1975), pp. 562-68.

[289] See also T.G. Muir and M. Vestrheim, "Parametric Arrays in Air with Applications to Atmospheric Sounding," 8e Symposium International sur l'acousticque non linéaire, *Journal de Physique* 41, Colloque C-8, suppl. au no. 11 (November 1979), pp. C8-89 to C8-94.

[290] For plane waves without absorption or depletion, see A.L. Thuras, R.T. Jenkins, and H.T. O'Neil, "Extraneous Frequencies Generated in Air Carrying Intense Sound Waves," *Journal of the Acoustical Society of America* VI (January 1935), pp. 173-80; for a bounded beam with absorption see Westervelt (note 288).

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.

A.4 Strong-Shock Regime[291]

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.

In strong shock, a similarity relation holds and state variables can be expressed in terms of the shock overpressure p_{Sh}—this pressure is measured in parallel to the propagation direction. Further relevant are the shock speed

$$\mathrm{v}_{Sh} = c_0\left[1+(\gamma+1)\,p_{sh}/(2\gamma P_0)\right]^{1/2} \qquad \text{(A-35)}$$

the absolute temperature T_{Sh} in the shock (T_0 refers to the medium in front)

$$T_{Sh}/T_0 = (1+p_{Sh}/P_0)\quad\left[2\gamma+(\gamma-1)\,p_{Sh}/P_0\right]/\left[2\gamma+(\gamma+1)\,p_{Sh}/P_0\right] \qquad \text{(A-36)}$$

the peak dynamic pressure exerted by the moving air immediately behind the shock

$$p_d = \rho u^2/2 = p_{Sh}{}^2/\left[2\gamma P_0+(\gamma-1)\,p_{Sh}\right] \qquad (u\text{: particle velocity}) \qquad \text{(A-37)}$$

and the peak reflected overpressure at normal incidence—this holds at a hard surface perpendicular to the propagation direction.

$$p_r = 2p_{Sh}+(\gamma+1)\,p_d \qquad \text{(A-38)}$$

For overpressures below about ten times atmospheric pressure, air can be treated as ideal gas of γ=1.4.[292] Thus, the dynamic pressure is maximally 2.5 times, and the reflected one 8 times the shock overpressure. Empirical formulas exist which include the effects from the exploded gases

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[291] Zel'dovich and Raizer (note 211); Whitham (note 280); S. Glasstone and P.J. Dolan, "The Effects of Nuclear Weapons" (Washington, DC: U.S. Government Printing Office, 1977) (ch. III); and Kinney and Graham (note 181).

[292] Effects of ionization and dissociation at higher pressures and temperatures can be included by using empirical values for the specific-heat ratio γ of 1.2 to 1.3, see Zel'dovich and Raizer (note 211), p. 95.

as well as of weak shock at larger distance. For a conventional explosion, the peak overpressure in the shock wave (spherical, in free air) is given by [293]

$$p_{Sh}(r)/P_0 = 808\,(1+r_{sc}/4.5\text{ m})^2 \Big/ \left[(1+r_{sc}/0.048\text{ m})^2(1+r_{sc}/0.32\text{ m})^2(1+r_{sc}/1.35\text{ m})^2\right]^{1/2} \qquad \text{(A-39)}$$

where P_0 is the ambient pressure in front of the shock and the scaled radius r_{sc} is derived from the actual value r by

$$r_{sc} = r\left[(\rho_a/\rho_0)/(W/1\text{ kg TNT})\right]^{1/3} \qquad \text{(A-40)}$$

Here ρ_a and ρ_0 are the ambient and sea-level densities, respectively, and *W* is the energy released in the explosion (note that 1 kg TNT=4.2 MJ).[294] This scaling holds for all explosions, from small to extremely large, and into the weak-shock region; the actual expressions for the overpressure, etc., vary, however, e.g., between a chemical and a nuclear explosion. For an explosion taking place at an ideally reflecting surface, the energy *W* has to be doubled.

The shock overpressures of 0.1 and 1 kg TNT exploded at sea level are shown in fig. A.2 a; here 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,[295] to about 200 m.

The duration t_d of the positive-overpressure part of the shock wave is given—for a chemical explosion—by [296]

$$(t_d(r)/\text{s})/(W/\text{kg TNT})^{1/3} = 0.98\,(1+(r_{sc}/0.54\text{ m})^{10}) \Big/ \left[(1+(r_{sc}/0.02\text{ m})^3)(1+(r_{sc}/0.74\text{ m})^6)(1+(r_{sc}/6.9\text{ m})^2)^{1/2}\right]. \qquad \text{(A-41)}$$

Fig. A.2 b shows this duration for 0.1 and 1 kg TNT. It is obvious that for small chemical explosions the pulse durations—at applicable distances—are on the order of milliseconds, thus in 2.5

[293] Kinney and Graham (note 181), p. 94.

[294] For a nuclear explosion where the masses of the explosive and neighboring air can be neglected the equation is different, starting immediately with an r^{-3} dependence: Kinney and Graham (note 181), p. 94.

[295] W.D. Ward, W. Selters, and A. Glorig, "Exploratory Studies on Temporal Threshold Shift from Impulses," *Journal of the Acoustical Society of America* 33 (6) (June 1961), pp. 781-93.

[296] Kinney and Graham (note 181), p. 97.

the damage thresholds for the short times apply. The curvature of the decrease of overpressure with time after passage of the shock front is a function of p_{Sh}, too. The total impulse per area exerted by a blast wave, i.e., the time integral over the sum overpressure during the positive phase for parallel incidence, is—again for a chemical explosion:[297]

$$(I/A)/(\mathrm{Pa\,s}) = 6.7\left(1+(r_{sc}/0.23\,\mathrm{m})^4\right)^{1/2} \Big/ \left[r_{sc}^{2}\left(1+(r_{sc}/1.55\,\mathrm{m})^3\right)^{1/3}\right] \qquad \text{(A-42)}$$

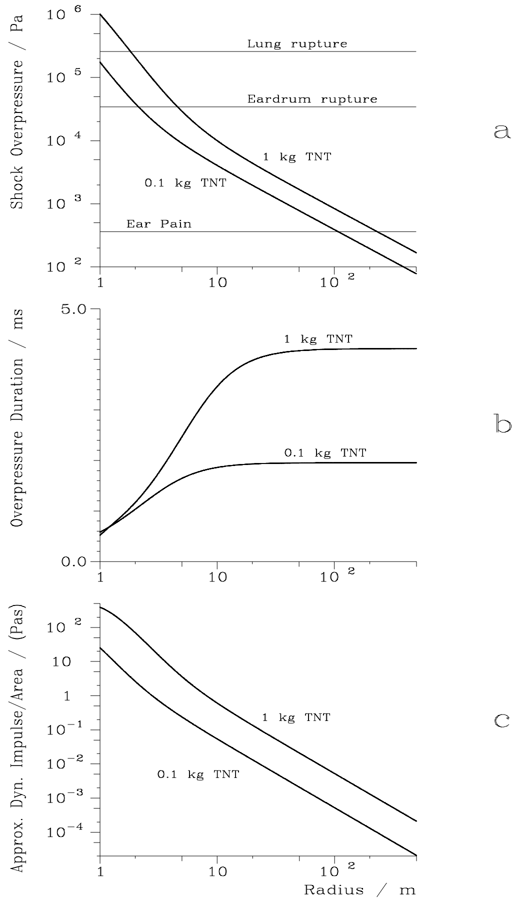

Fig. A.2 Shock overpressure p_{Sh} (a), overpressure-pulse duration t_d (b), and approximate dynamic-pressure-caused impulse per area for unity drag coefficient (c), versus distance r for conventional explosions of 0.1 and 1 kg TNT at sea level in free air. The strong-shock regime with r^{-3} pressure 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 c_D.

For determining the total blast loading on some object one has to consider the time courses of the respective pressures, as the shock wave reflects on the front, passes around the sides and diffracts along the back surface, and form the time-dependent sum. For a rectangular body hit normally, the lateral contributions cancel and the back one subtracts from the front one. For human heads or bodies as they are relevant here, however, the respective propagation times are very short (e.g., 0.5 ms with a shock speed of 0.5 km/s and a distance of 0.25 m for a standing

[297] Kinney and Graham (note 181), p. 98. Note that this equation gives about 20% higher *I/A* values than listed in their table XI.

person). Thus, the body is very fast 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. For a simple conservative estimate, one can neglect the curvature of the dynamic-pressure time course and assume the duration t_d to hold for its positive part too. With a linear decrease from the maximum p_d to zero during that time, the time integral over the drag force per area acting on a body of drag coefficient c_D and area A becomes

$$\int F_D dt / A = c_D I_D / A \cong c_D p_d t_d / 2 \qquad \text{(A-43)}$$

This is shown for c_D=1 in Fig. A.2 c.

To give numbers for the case of 1 kg TNT in fig. A.2, at 5 m distance the peak overpressure is 29 kPa, the shock moves with 383 m/s, the overpressure lasts 2.5 ms, the peak reflected and dynamic pressures are 65 and 2.9 kPa, respectively, the side-on impulse per area is 39 Pas, and the approximate drag impulse per area is—for unity drag coefficient—3.6 Pas.

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.[298] However, at the margin of an initially bounded shock wave no power flows in from beyond the margin, and there is a continuous loss of excitation outward. The outer parts of the front do travel more slowly, but there is no corrective mechanism to turn them inward again. Diffraction of shock waves in case of shock-tube widening, especially around a 90° corner, is a standard problem in books on shock waves; an approximate treatment of the general case uses ray tubes which widen or narrow according to the external geometry and local shock motion.[299] Schlieren photographs and numerical modeling of 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, of course there at much reduced pressure and speed.[300]

For the present application the question is whether considerable shock energy can be focused into a narrow cone, avoiding distribution over a full sphere. Quantitative analysis requires a study on its own, however, some qualitative considerations are possible. The usual r^{-3} decrease of shock pressure is due to the distribution of the explosion energy over the volume of a sphere.[301] From an energy consideration, thus, the distance dependence for shock waves propagating as bounded beams of constant width, as in a shock tube, would be in proportion to

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[298] Whitham (note 280), section 8.8.

[299] Whitham (note 280), ch. 8.

[300] See, e.g., S.B. Bazarov et al., "Three-Dimensional Shock Ejection from a Channel," in R. Brun and L.Z. Dumitrescu (eds.), *Shock Waves @ Marseille IV* (Berlin: Springer, 1995), pp. 135-38.

[301] Note that in strong shock the overpressure is close to the absolute pressure which is proportional to the mean energy density. This is different from the weak-shock and linear-acoustics regimes where the overpressure is small versus the absolute pressure and the energy in the wave is proportional to the overpressure squared.

$1/r$. Should a bounded plane shock wave start from a surface large against a typical wavelength in the spectrum of the pulse, the radius of the strong part of the wave would at first remain about constant, and the mentioned stabilization would be at work there. The volume heated most would increase linearly with distance, and the on-axis shock pressure would decrease with 1/r. Due to diffraction with loss on the margins, and faster propagation on the axis, after some distance the wave fronts would become curved even on the axis, propagation would change to an approximately spherical mode and shock overpressure would—if strong shock still prevails—again change to r^{-3} decrease. Ultimately, about $1/r$ dependence would hold again as overpressures become smaller than normal pressure. 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 still bounded at, say, 50 m distance which was produced by a 1 m wide source.[302]

A.5 Infrasound Beam and Other Propagation Estimates

With a transmitter diameter of D=3 m (radius a=1.5 m, area A=7.1 m^2) a baffle of much larger size is excluded, and the source acts like an unflanged pipe; therefore in eq. (A-10) the pressure has to be halved. With an acoustic power of P=10 kW the intensity is I_{rms}=1.4 kW/m^2, with (A-6) the rms pressure at the source is p_{rms}=0.77 kPa (level 152 dB), the pressure amplitude p_0=1.1 kPa. The Mach number from (A-5) and (A-14) is M=0.011. With a wavelength of λ=17.2 m (frequency ν=20 Hz), the product ka in (A-10) is 0.55, far below $\pi/2$, so the far-field intensity is the same in all directions, and the infrasound energy spreads over a full sphere, or close to the ground over a half sphere.

Parallel wave fronts will leave the source area, but they will become spherical immediately. To estimate whether non-linear effects play a role, I assume an emitting half sphere of radius r_0=a equal to the radius of the circular source with the same intensity (i.e., double total power), and neglect the ground influence. Then the dimensionless number Z_0 according to (A-26) becomes Z_0=0.005, and the shock-forming radius r_p according to (A-29) is practically infinite—no shock will form. At r=50 m distance the intensity and pressure will be [from (A-13) times 1/4 and (A-6)]:

$$I_{\text{rms}}(50\text{ m}) = 24\text{ mW / m}^2, \quad p_{\text{rms}}(50\text{ m}) = 3.2\text{ Pa} \qquad \text{(A-44)}$$

(level 104 dB).

With ν=100 Hz, λ=3.4 m, and the same emitter size of D=3 m, ka in (A-10) is 2.75, somewhat above $\pi/2$, but still there is no diffraction null, and in forward direction there is essentially spherical propagation. The number Z_0 becomes 0.025 and there is still no shock at finite distances. Thus, again from (A-13) times 1/4 and (A-6), the intensity and pressure at 50 m distance are

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302 Note that for the different problem of a shaped charge the hot-liquid-metal projectile has been said to remain effective over a distance of a hundred times the diameter of the explosive if its funnel-shaped deepening is shallow: G.I. Pokrowski, *Explosion und Sprengung* (Moscow/Leipzig: MIR/Teubner, 1985), p. 51. But this is of course a material projectile and not a shock wave in air.

$$I_{\text{rms}}(50\text{ m}) = 0.60\text{ W / m}^2, \quad p_{\text{rms}}(50\text{ m}) = 16\text{ Pa} \qquad \text{(A-45)}$$

(level 118 dB). A threshold level of 140 dB (p=200 Pa, I=100 W/m^2) is crossed at distance r=4.0 m.

At ν=500 Hz, λ=0.69 m, one may be motivated to work with smaller, easier-to-handle emitter sizes, but first let us stick with *D*=3 m diameter. Now, with *ka*=9.2, there is a first null at angle φ_1=16°, see (A-11). The beam diameter will remain about constant up to a distance

$$x_{sp} = a / \tan \varphi_1 \qquad \text{(A-46)}$$

x_{sp}=5.2 m in this case, after which spherical divergence will become dominant. This is a case where both effects, non-linear propagation and diffraction, contribute (*N* from (A-31) is 0.82), and no simple calculation of intensity versus distance is possible. In the case of plane waves, shock would occur after (A-18) only at x_p=8.5 m; in reality, spherical divergence would start clearly before. An upper bound for the intensity can be gained by assuming that no shock develops at the spherical part as well. Then again the linear-diffraction dependence (A-13) times 1/4 can be used and for the intensity and pressure at 50 m distance

$$I_{\text{rms}}(50\text{ m}) \le 15\text{ W / m}^2, \quad p_{\text{rms}}(50\text{ m}) \le 79\text{ Pa} \qquad \text{(A-47)}$$

hold—i.e., a level below 132 dB. With shock, lower values would hold. This could be in the discomfort region, but would clearly remain below the thresholds for aural pain and damage for short-term exposure for unprotected ears.

If a smaller source were used, say *D*=1 m diameter, the source intensity would become I_{rms}=12.7 kW/m^2, the pressure p_{rms}=2.3 kPa (level 161 dB, p_0=3.3 kPa), the Mach number *M*=0.032. A much larger baffle is excluded; a slightly larger one would not be worth the trouble of handling (instead, one would rather use a larger emitter in the first place). Thus, still the factor of 1/2 has to be applied to (A-10).

Again at 500 Hz, the beam angle would be about three times higher, the diffraction null would appear under φ_1=57°. Spherical divergence would become important already at x_{sp}=0.33 m, so that non-linearity can be estimated with spherical waves (*N*=2.5). The number Z_0 from (A-26) becomes 0.125, and shock would start only at 1.5 km. Thus, linear diffraction would prevail and the intensity and pressure at 50 m distance would ensue from (A-13) times 1/4 and (A-6) to

$$I_{\text{rms}}(50\text{ m}) = 1.7\text{ W / m}^2, \quad p_{\text{rms}}(50\text{ m}) = 26\text{ Pa} \qquad \text{(A-48)}$$

level 122 dB—touching on discomfort but clearly below the thresholds of pain and short-term-exposure damage for unprotected ears.

At ν=2 kHz, the beam becomes narrower again, with the first null at φ_1=12°, and spherical divergence from (A-46) starting only at x_{sp}=2.3 m (*N*=0.039). For the plane-wave case in front of that, shock develops according to (A-18) at x_p=0.71 m, clearly in front of the transition to spherical propagation. The peak pressure will decrease over that distance—with (A-21), neglecting the tanh parenthesis—to about

$$p(2.3\text{ m}) = 0.76\text{ kPa} \qquad \text{(A-49)}$$

Here it is not easy to compute in which way an already shocked wave would change to spherical propagation. For an upper bound, I assume that the spherical wave would start anew with sinusoidal form at $x_{sp}=r_0=2.3$ m. Then from (A-26) the number is $Z_0=0.54$, spherical shock would develop at $r_p=15$ m. From (A-25), again neglecting the tanh expression, the peak pressure at 50 m distance results to

$$p(50\text{ m}) = 13\text{ Pa} \qquad \text{(A-50)}$$

Since in reality the spherical wave would be shocked from the beginning at $x_{sp}=2.3$ m, the rms intensity and pressure at 50 m are

$$I_{rms}(50\text{ m}) < 0.21\text{ W / m}^2, \quad p_{rms}(50\text{ m}) < 9.4\text{ Pa} \qquad \text{(A-51)}$$

the level below 113 dB. This is certainly loud, but clearly even below the discomfort level for unprotected hearing.

At $\nu=10$ kHz, again P=10 kW emitted from a D=1 m source, the first diffraction null from (A-11) is at $\varphi_1=4.8°$, and spherical divergence from (A-46) starts at $x_{sp}=6.0$ m ($N=0.0062$). The first plane wave becomes shocked (A-18) already at $x_p=0.14$ m. Until the end of plane-wave propagation, the peak pressure will decrease—with (A-21), neglecting the tanh parenthesis—to about

$$p(6.0\text{ m}) = 76\text{ Pa} \qquad \text{(A-52)}$$

Using the same conservative assumption of a spherical wave starting here with $r_0=x_{sp}=6.0$ m, but reverted to sinusoidal form, the number $Z_0=0.69$, and spherical shock would start at $r_p=25$ m. However, here it would end at $r_{lim}=40$ m ($Z_{lim}=1.91$) after (A-30). Then similarly as above from (A-25) the peak pressure at r_{lim} becomes

$$p(40\text{ m}) = 4.8\text{ Pa} \qquad \text{(A-53)}$$

from which normal spherical 1/r decrease would follow, down to a peak value at 50 m distance

$$p(50\text{ m}) = 3.9\text{ Pa} \qquad \text{(A-54)}$$

corresponding to bounds for the rms intensity and pressure at 50 m of

$$I_{rms}(50\text{ m}) < 18\text{ mW / m}^2, \quad p_{rms}(50\text{ m}) < 2.7\text{ Pa} \qquad \text{(A-55)}$$

a level under 103 dB, even deeper below the discomfort threshold for unprotected hearing.

Using a standard value of b=3·10^{-4} kg/(sm), the absorption coefficient at 10 kHz from (A-17) becomes 0.012 m^{-1}, yielding an additional attenuation by a factor 0.5 over 50 m. Only at even higher frequencies would absorption contribute more drastically over such distances.

It has to be repeated that these are only estimates, and that detailed calculations would be required for reliable quantitative results in cases where non-linear and diffraction effects are about equally important. One should also keep in mind that absorption—important for higher frequencies and in particular for shocked propagation via the front thickness and the distance to the low-amplitude end of shock—changes strongly with humidity and frequency. However, there is no doubt on the impossibility of a narrow sound beam at low frequencies. And, as demonstrated, the sound pressure at some distance cannot easily be increased by increasing the frequency and/or the intensity of the source, since both tend to produce or enhance shocked propagation, which leads to much stronger losses.

A.6 Infrasound from Non-Linear Superposition of Two Ultrasound Beams

In case of non-linear difference-frequency conversion in *air*, eq. (A-34) shows that in the case of plane waves the sound pressure at the difference frequency is limited by the starting pressure p_0 times the frequency ratio $(\nu_1-\nu_2)/[(\nu_1+\nu_2)/2]$, times a factor on the order of 1. With $\nu_1-\nu_2$=20 Hz and $\nu_1\approx\nu_2$=16 kHz, this ratio is 0.00125 (-58 dB in level).

For assessing whether the plane-wave assumption is appropriate, let us assume a source (e.g., reflector) diameter of 1 m. Then, according to eq. (A-11)—which should be acceptable at least for a rough estimate of diffraction also in the non-linear case—with a wavelength of 0.21 cm for 16 kHz, in the far field the irradiated spot will grow with a half angle of 0.026 rad=1.5°; in 50 m distance the diameter will be 2.6 m, about twice the one of the emitter. The wave would optimally be emitted with approximately plane wave fronts, without focusing to close distance; the beam width would somehow grow from its initial width of 1 m to 2.6 m. Even taking into account non-linear effects, it seems improbable that drastic deviations of the beam width from 1-2 m will occur, the waves will remain approximately planar without large losses due to beam spreading. Should spherical spreading become important before the difference-frequency wave saturates, its pressure would remain smaller.

For non-linear conversion in the *ear*, a sound-pressure/inner-ear transfer-factor reduction by 1/20 is assumed for $\nu\geq$16 kHz. The static-pressure—umbo-angle relationship derived from measurements of human cadavers is linear for underpressures to at least -600 Pa; for overpressures, however, the function behaves non-linearly above about 20 Pa and turns to a kind of saturation (fig. A.3 a).[303] For a simple estimate, I assume that the linear dependence continues to arbitrary negative pressures—this is conservative because it neglects limits on outward membrane travel—and that the curved part is replaced by a corner and a constant saturation value. Thus, the dependence of the umbo angle φ on momentary pressure p is given by

303 H.G. Kobrak, "Construction Material of the Sound Conduction System of the Human Ear," *Journal of the Acoustical Society of America* 20 (1948), pp. 125-30; for the approximate equation see H.E. von Gierke and D.E. Parker, "Infrasound," ch. 14 in W.D. Keidel and W.D. Neff (eds.), *Auditory System—Clinical and Special Topics*, *Handbook of Sensory Physiology*, vol. V/3 (Berlin: Springer, 1976), section VII, fig. 2 (however, their 2nd to 4th coefficients seem wrong). Note that also here the middle-ear muscle reflex was not at work, rendering the relation used more conservative.

$$\varphi = \begin{cases} a\,p & \text{for } p < p_{s0} \\ \varphi_s & \text{for } p > p_{s0} \end{cases} \qquad \text{(A-56)}$$

(for low frequencies), with a slope of the linear part a=2.0 mrad/Pa, a saturation angle φ_s=4.5 mrad, and a corner pressure p_{s0}=227 Pa (fig. 3 a).[304]

Fig. A.3 Estimating the equivalent low-frequency pressure amplitude induced by a saturation-type input-output relation in the middle ear. a) Umbo angle versus pressure on the tympanic membrane as derived from static measurements on human cadavers (dotted) and approximation by a linear and a constant section (full line). b) Time course of umbo angle for one period of an impinging sawtooth wave if peak is below (left) or above (right) the saturation value. c) Replacing the triangular/clipped half waves by rectangular shapes of equal amplitude allows a simple calculation of the average angle over one period: it is half the difference $\Delta\varphi$ between the linear and clipped maximum values of the positive half wave. For a high-frequency wave with amplitude modulation, the resulting low-frequency wave would follow this average, i.e., it would move with an amplitude of $\Delta\varphi/4$ about its own mean value of $-\Delta\varphi/4$.

A high-frequency wave of sufficient intensity would in any case arrive with a shocked, sawtooth shape. If the peak pressure is below p_{s0}, the umbo angle is proportional all the time; for a higher amplitude, the positive half wave is clipped at φ_s (fig. A.3 b). The low-frequency wave is formed by averaging the high-frequency signal, the amplitude of which changes with the modulation, or the beat between the two neighboring frequencies. For a simple estimate replace the positive and negative half waves by squares of equal amplitude (fig. A.3 c; exact calculation with triangular shapes shows that this overestimates the magnitude by a factor $\geq$ 2). Then the

[304] Numbers converted from the units (arc minutes and cm H_2O) given by v. Gierke and Parker (note 303).

momentary average value of φ—computed over just one period—is zero as long as the impinging amplitude is below p_{s0}, and otherwise will be minus one half of the clipped part Δφ of the positive half wave. (Unlike the case of conversion in the air, this is independent of the values of low and high frequency.) The average angle moves between -Δφ/2 and zero—about sinusoidally for sinusoidal modulation signal, or similar to a two-way-rectified signal for difference-frequency production. The low-frequency excitation varies about its own average value of -Δφ/4 with an amplitude of Δφ/4. For equal auditory effects, as from direct excitation with an infrasound wave of amplitude p_{NF}, the angle amplitudes should be equal:

$$\Delta\varphi / 4 = (a\ p_{HF} - \varphi_s) / 4 = a\ p_{NF} \qquad \text{(A-57)}$$

(Since the all average angle values are in the negative, linear region, the infrasound signal is not affected by saturation itself). Solving for the high-frequency amplitude p_{HF}, one gets

$$p_{HF} = (4a\ p_{NF} + \varphi_s) / a \qquad \text{(A-58)}$$

Assuming an infrasound threshold level of 140 dB ($p_{NF}=2^{1/2}\cdot 200$ Pa) and using the constants from (A-56), the required high-frequency amplitude becomes p_{HF}=1.36 kPa, and the level (with the rms pressure of 959 Pa) becomes 154 dB. With the weakening factor of 20 (26 dB) finally a required rms ultrasound pressure of 19.2 kPa (180 dB) results.

As demonstrated for the case of conversion in air in 5.1.2, focusing cannot be used to drastically reduce the beam width, and increase the intensity, over distances of several tens of meters. Assuming the plane-wave case of eqns. (A-14) to (A-24) and using $b=5\cdot 10^{-4}$ kg/(sm), a 16-kHz wave of $2^{1/2}\cdot 19$ kPa=27 kPa starting amplitude (M=0.20, Re=541) will become shocked at 1.4 cm (less than one wavelength). The third, amplitude-invariant stage is reached in 39 m with an amplitude of 27 mPa (60 dB).

A.7 Plasma Created in Front of Target, Impact as by Blunt Object

Plasma, i.e., ionization of air, occurs in weak form first with nitric oxide NO (with an ionization potential of E_{ion}=9.5 eV), with considerable ion densities at temperatures above about 2000 K; stronger effects occur above 5000 K.[305] Inversion of eq. (A-36) allows to compute which strong-shock overpressures would be required to achieve such temperatures; the results are $p_{Sh}=35\ P_0$ and $97\ P_0$ (3.6 and 9.8 MPa), respectively. The Boltzmann factors $\exp[-E_{ion}/(kT)]$ are $1.2\cdot 10^{-24}$ and $2.7\cdot 10^{-10}$, respectively.

Concerning blunt-object trauma by a shock wave, the time integral over the drag force is given approximately in eq. (A-43). A limit for injury can be gained from the analogy to whole-body impact on a hard surface. If deceleration to zero velocity occurs in less than 5 ms, first injuries will occur if the speed is 3 m/s.[306] Let us assume a threshold for blunt-object trauma of

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[305] V.P. Korobeinikov, *Unsteady Interaction of Shock and Detonation Waves in Gases* (New York: Hemisphere Publishing Co., 1989), pp. 1-3.

[306] A.E. Hirsch, "The Tolerance of Man to Impact," *Annals of the New York Academy of Sciences* 152 (Art. 1) (1968), pp. 168-71.

one third of that, Δv=1 m/s as the time integral over the deceleration. The impulse transferred to the large obstacle is

$$I = m\Delta v \quad \text{(A-59)}$$

with m=70 kg thus I=70 kgm/s. If exposed to the drag force of a shock wave in a fixed position, the body should not be injured so long as the time integral of the force stays below that limit. With the approximation of (A-43)

$$\int F_D dt = c_D A(I_D / A) \cong c_D A p_d t_d / 2 \quad \text{(A-60)}$$

thus, with a body area of A=1 m^2 and a drag coefficient c_D=1, the limiting value of drag impulse per area is

$$70\ Pas \cong (I_D\ /\ A) \cong 1\ p_d t_d\ /\ 2 \quad \text{(A-61)}$$

For a typical positive-overpressure duration of say, t_d=3 ms (see fig. A.2 b), the limit peak drag pressure becomes p_d=47 kPa.[307] Solving (A-37) for the shock overpressure gives p_{Sh}=125 kPa. With a spherical explosion of 1 kg TNT, this value occurs at about 3 m distance (see fig. A.2 a).

[307] To be more exact, including the effects of smaller duration t_d at shorter distance, one could—for given explosive energy—gain the distance where the drag impulse per area equals the limiting value from fig. A.2 c, and then look up the overpressure there from fig. A.2 a (or compute it from (A-37). This would yield even higher overpressures.