Danger of auditory impairment from impulse noise: A comparative study of the CHABA damage-risk criteria and those of the Federal Republic of Germany

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(Received 2 February 1979; accepted for publication 5 September 1979)

On the basis of the impulse diagrams of various weapons and many audiometric tests, the CHABA impulse-noise damage-risk criteria (DRC) are compared with those of the Federal Republic of Germany. Both DRC indicate maximum permissible exposures in terms of peak-pressure level and of effective duration. Both DRC aim to protect 95% of the exposed population from permanent auditory damage. The computation of the effective duration differs between the CHABA DRC and the German DRC, and it generally results in a longer effective duration for CHABA. The current study is based on the results for more than 10000 soldiers, who were audiometrically tested in a mobile monitoring station before firing practice and beginning 2 min after exposure until complete recovery. In a special study, it was possible to compare the results for 478 German soldiers and to evaluate the relative value of the CHABA DRC and the German DRC. This comparison showed that the CHABA DRC are too restrictive, permitting unnecessary "less maximum permissible load" than the German DRC. Moreover, owing to the large variability in TTS_2, measurement of the whole recovery time beginning 2 min after exposure has a greater predictive value. Therefore, recovery time should be used in the evaluation of the DRC.

PACS numbers: 43.66.Ed, 43.66.Sr, 43.50.Qp [BS]

INTRODUCTION

The increase in the firing power of modern weapons results in ever increasing intense acoustic effects. Naturally, everything possible must be done to avoid auditory damage to soldiers exposed to these sounds. The Federal Ministry of Defense, Federal Armed Forces Directorate of Medical and Health Services, has, accordingly, supported research to investigate means for avoiding such hearing damage. This paper presents some of the results of this research.

I. CURRENT DAMAGE-RISK CRITERIA

In the United Kingdom and the USA, the CHABA diagram (Coles *et al.*, 1968; Ward, 1968) is generally referred to for the assessment of the danger of auditory damage from exposure to impulse noise, whereas in the Federal Republic of Germany (FRG) a different diagram of exposure limits is used. The German diagram (Pfander, 1972, 1975) is based on the assumption that no permanent damage is to be expected from acoustic exposure if only 5% of the persons exposed still show a temporary threshold shift (TTS) 24 h after the event and this TTS disappears within two weeks (provided that there is no further detrimental acoustic exposure). Of the persons exposed, 95% must show no evidence of any change in their hearing ability 24 h after exposure. A permanent threshold shift (PTS) cannot be tolerated. The relation between TTS_2 (the TTS measured 2 min after acoustic exposure) and recovery time to the pre-exposure threshold levels and their use as criteria for assessing auditory damage risk are discussed at the end of this article. In its original presentation (Coles *et al.*, 1968), the CHABA diagram proposed protection for 75% of the exposed population. Its final presentation (Ward, 1968) sought to protect 95% of the population. The exposure limits, given as boundary lines, of the CHABA diagram form the basis for the present, comparative study.

In the German diagram on damage-risk criteria, the slope of the limiting lines is such that the halving parameter for the number of impulses and for the effective duration is $q = 3$ (equal energy). The halving parameter of $q = 3$ means that an effective duration that is halved has the same effect on a human being at a level that is 3 dB higher. In the CHABA diagram, the halving parameter for the duration of the impulses is $q = 2$ and for the number of impulses is $q = 1.5$.

Although the effect of an impulse noise on the human ear is determined primarily by the peak pressure, the time history of the noise is also important.

The various problems encountered in the acoustical measurement of impulses have been dealt with in detail by Coles *et al.* (1968) and by Pfander (1975). Our own earlier measurements (Series 2 through 6 of Table I) of the pressure–time course were made with a high-pressure microphone (Massa 141) and a sound-level meter (General Radio 1551) as amplifier. More recent measurements (Series 1 of Table I) have been made with a Brüel and Kjaer 1/8 in microphone (4138) with preamplifier (2618) and sound-level meter (2606) as amplifier. In all measurements, the microphone was positioned for grazing incidence. The recording was achieved by photographing from the screen of an oscilloscope. The resulting oscillograms permitted evaluation of the peak pressure as well as the so-called effective duration.

CHABA distinguishes between two methods for determining the effective duration, the A time and the B time (Fig. 1). A time is measured from the beginning of the impulse up to the first zero crossing. This exclusive emphasis on the first peak may be justified in a few special cases, but few real noises are of this idealized type. For example, A time does not specifically allow

[a] Directed by Dr. Friedrich Pfander.

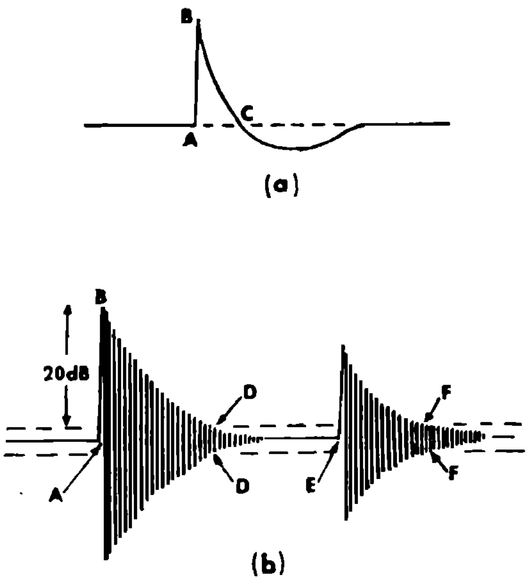

FIG. 1. Idealized oscilloscopic waveforms of impulse noises. Peak level: pressure difference AB. Rise time: time difference AB. (a) A duration: time difference AC. (b) B duration: time difference AD (+ EF when a reflection is present).

for subsequent oscillations (e. g., reflections), which may even be significantly higher than the first one.

B time is measured between the 20-dB down points on the waveform. That is, duration is measured from the time at which the level first reaches a value 20 dB below the peak level to the last point at which the impulse level is just 20 dB below the peak. (Note that both positive and negative levels are considered.) Special allowance is made for any separate reflection wave.

The FRG uses a different method, which we refer to as C time (Fig. 2). C time is similar to B time, except that the criterion level is 10 dB down from the peak instead of 20 dB. Effective durations do not have to be determined in this way. They merely provide a convenient working hypothesis for using damage-risk criteria to avoid damage to the auditory organ.

As long as we do not know exactly how an impulse affects the human ear physically, the only way to evaluate these three proposals (A, B, and C time) is to subject as many soldiers as possible to audiometric tests before and after firing practice with a range of weapons. Such field tests have been carried out (Pfander, 1973). The soldiers were exposed to the acoustic events with-

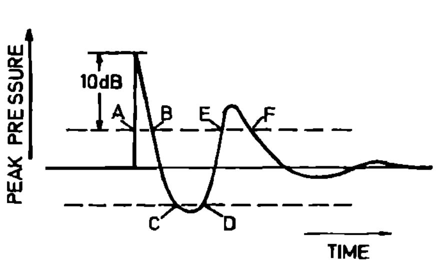

FIG. 2. Idealized representation of how the pressure of an impulse changes as a function of time. Effective duration (C time) is the sum of the durations AB+ CD+ EF.

out protection only in the first few years of these series of tests. During the past ten years, audiometric tests have been carried out (with a few unintentional exceptions) only on soldiers wearing hearing protectors during firing.

As shown below, in all the firing practices during the last few years, specifically connected with audiometric tests, the protection level of 95% aimed for in the German damage-risk criteria has always been achieved (once hearing protection became mandatory).

II. IMPULSE-DIAGRAM COMPARISON

Figure 3 contains many values measured in accordance with the C time method for one round. Various impulse diagrams from the last few years that were as typical as possible were evaluated in order to determine the appropriate C time in each case. In most cases, the measuring microphone was placed in positions where the operating personnel were subsequently to be located, but sometimes also in locations (close to the muzzle) where a gunner would normally not be found. Figure 3 contains two lines which, in accordance with the diagram on damage-risk criteria, are to be regarded as limiting lines for unprotected and protected ears (25-dB hearing protectors, i.e., at least 25-dB attenuation at frequencies of 1 kHz and higher).

For the few measured values that fall below the lower limiting line, hearing protectors would be unnecessary. In most cases, however, hearing protectors are absolutely essential. Since the measured values—except for the nine numbered points—lie below the upper limiting line, in all these cases the hearing protector is adequate for one round. The points numbered one to nine were based upon impulse diagrams recorded from microphones located, for example, near the muzzles of weapons or along the projectile trajectory. In no case do they correspond to acoustic exposures to which personnel were subjected.

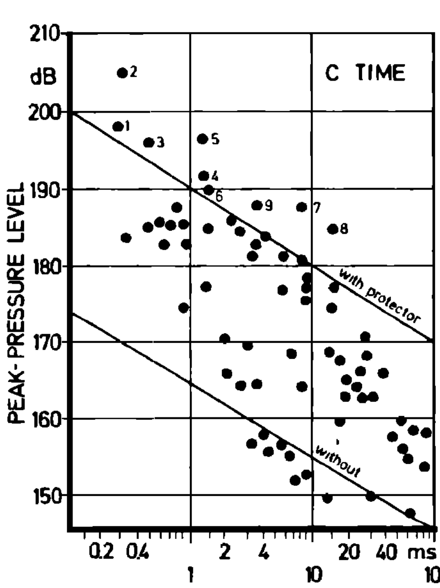

FIG. 3. Evaluation of the C time for 66 impulse diagrams.

Not only the C time, but also the B time was determined from each of the selected diagrams; Fig. 4 gives these B times. The two lines in Fig. 4 are to be regarded, according to CHABA, as the limiting lines of a single shot. Although CHABA does not give a limiting line for exposures with hearing protectors, a second line was included, by analogy with the German diagram, and in accordance with a hearing protection attenuation level of 25 dB (as defined above). The upper line again applies to protected ears, the lower to unprotected ears.

More measured values lie above the upper limiting line in Fig. 4 than in Fig. 3. According to Fig. 4, during these firing practices the acoustic exposure would be too great despite the 25-dB hearing protection. A comparison of C and B times shows that the CHABA curve, with its longer effective duration and its slope of $q = 2$, represents a more stringent yardstick, permitting less maximum stress for short durations, than the German diagram on damage-risk criteria with C time and $q = 3$.

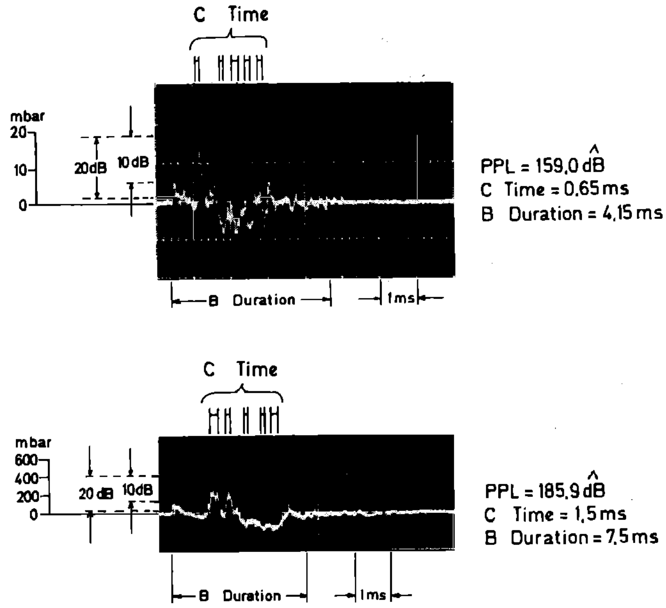

FIG. 5. Two examples of the evaluation of B time and C time for typical impulse oscillograms. Top diagram is for rifle A; bottom diagram is for the 84-mm-held antitank weapon.

III. DIAGRAM COMPARISON AND AUDIOMETRIC TESTS DURING FIRING PRACTICE

All tests in the FRG took place during scheduled firing practice by the Federal Armed Forces. If, in the interest of the audiometric testing of the soldiers, it seemed necessary to do so, interruptions of the exercise were discussed and effected in conjunction with the range control.

A test vehicle developed by Pfander, a mobile audiometer ("audiomobile"), was available for carrying out the mass audiometric tests and was equipped with four "Atlas Gross-audiometer EM 40" audiometers and four audio booths. This vehicle, with its own power supply, made it possible to drive to the locations earmarked for firing practice and to make audiometric tests 2 min after acoustic exposure. The tests were carried out in the frequency range from 60 Hz to 8 kHz at the customary octave intervals between 60 Hz and 1 kHz and at half-octave intervals between 1 and 8 kHz. Prior to each firing session, a complete audiogram from 60 Hz to 8 kHz was recorded for every soldier involved in any way—particularly for the training personnel—and after an otological examination.

The threshold measurements were made, in accordance with usual international procedures, by a trained examiner on one of the four audiometers (Lehnhardt, 1978; IEC Publication 177, 1965). The level of the test tone was increased in 5-dB steps until the subject signaled, by pressing a button that turned on a small lamp,

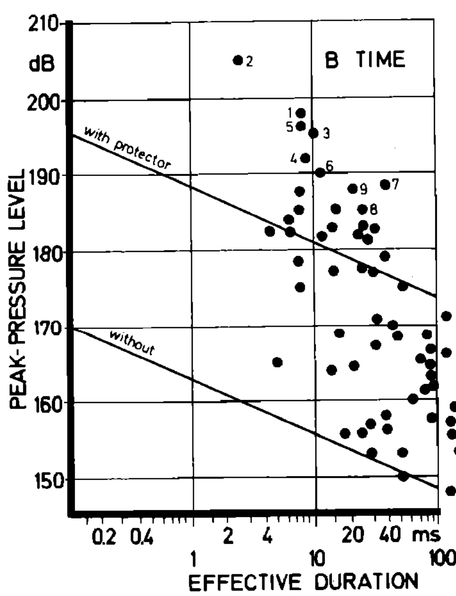

FIG. 4. Evaluation of the B time for the same 66 impulse diagrams as in Fig. 3.

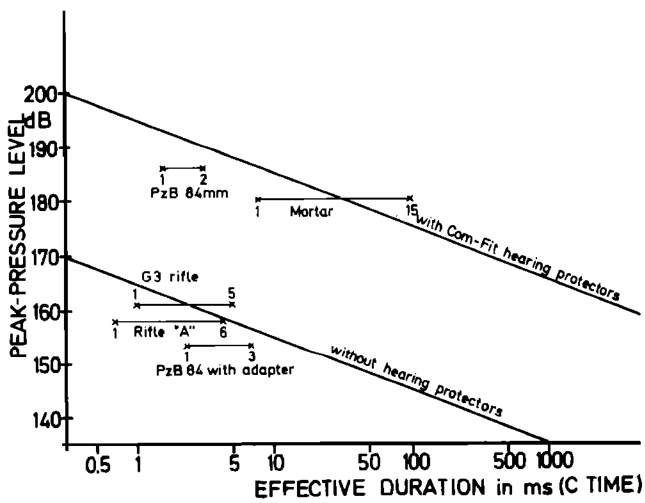

FIG. 6. Tolerance limits for the FRG, with and without heavy protectors, for the avoidance of hearing damage. Crosses are the measured values for five different weapons fired once and fired from two to fifteen times (as indicated). Values for more than one round were obtained by summing the values for individual rounds.

TABLE I. Comparison of B- and C-time computations for six firing practices. (Different soldiers were tested for each of the five different weapons. Only in Series 5 and 6 were the same soldiers tested in both series. In Series 1, no hearing protection was needed because the German DRC limit was not exceeded; in Series 2 and 3, hearing protection was not used because these series were carried out before hearing protection had become mandatory.)

Series No.	Acoustic exposure	Number of rounds	Hearing protection	Peak pressure level in dB	Mean values C duration in ms	B duration in ms	Number of test persons	Persons with prolonged recovery time (more than 24 h)
1	Rifle *A*	6	without	158.3	6×0.66 = 3.96	(6×) 4.2	103	<5%
2	*G* 3-rifle	5	without	160.8	5×0.97 = 4.85	(5×) 6.26	78	>15%
3	84 mm hand-held antitank weapon with subcaliber adapter	3	without	154	3×2.2 = 6.6	(3×)12	97	<5%
4	84 mm hand-held antitank weapon	2	with Com-Fit	186	2×1.5 = 3	(2×) 7	100	5%
5	Mortar	1	with Com-Fit	180	7	35	100	<5%
6	Mortar	15	with Com-Fit	180	15×7 = 105	(15×)35	98	>8%

when he first heard the tone. Measurements were repeated at each test frequency as many times as necessary until a clear threshold evaluation had been achieved. The subject sat in the soundproof booth.

Immediately after firing (normally after about two minutes), an initial control audiogram was taken for each participating soldier; this test was carried out at the same place and by the same examiner as the pretest. In this way, some sources of possible variation in the measured value were eliminated in the comparison "before-and-after" firing.

The audiometric check always began in the high-frequency range so as to record as quickly as possible any TTS that might be present. If TTS was found (at any frequency), audiometric tests were carried out continuously until the auditory threshold returned to the initial value that existed prior to firing. In this way, it was possible to ascertain in each individual case the recovery time, i.e., the end of the TTS.

Initially, these checkups took place regularly at approximately 3-min intervals. If the original auditory threshold was not reached after half an hour for any one of the test frequencies, another measurement was then made every half hour. If recovery was still not complete after 3 h, another examination was made after about 12 to 24 h and, where necessary, this was repeated after about two weeks. Approximately 100 soldiers participated, when possible, in the single firing rounds.

Impulse measurements were made simultaneously with firing. The measuring microphone was placed near the ears of the persons subjected to acoustic exposure in such a way that each particular exposure could be directly related to the audiometric test that took place after firing. Figure 5 shows examples of the B- and C-time computation of two typical impulse diagrams. Table I presents the results of six series of measurements, chosen from a large number carried out over a period of more than 20 years on 10000 soldiers. These six series were chosen because they permitted a precise comparison of CHABA's B time and the German C time, and because audiometric recovery had been followed over a sufficiently long time span. The test per-

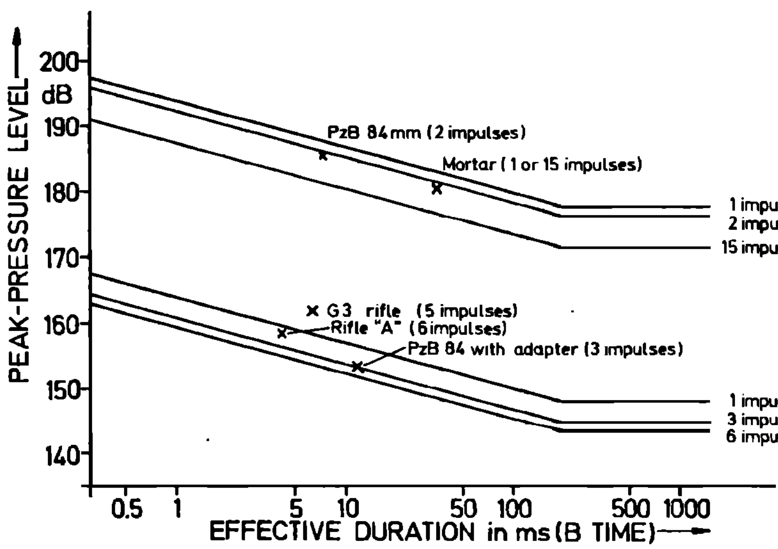

FIG. 7. CHABA damage-risk criteria for impulse noise. Crosses are the values for single shots evaluated, according to CHABA's B time, for the same five weapons as represented in Fig. 6. For more than one round, parallel limiting lines are displaced downward. As in the FRG diagram (Fig. 6), the limiting lines are placed 30 dB higher if hearing protectors are used.

sons indicated in Table I were all different except those subjected to the mortar fire; there the same persons were exposed to one round on one day and to 15 rounds on another day.

These results have now been incorporated into the diagram on damage-risk criteria of the FRG (Fig. 6) and the CHABA diagram (Fig. 7). It is clear that for rifle A the measured value of six rounds is below the limiting line of the German diagram without hearing protection, whereas the value is above CHABA's permissible limiting line. In fact, our audiometric tests following firing practice involving six rounds reveal that this stress is tolerable (i.e., produces prolonged recovery time in less than 5% of the subjects) without hearing protection. An acoustic exposure of five rounds from the G-3 rifle without hearing protection is above the limiting line of the German diagram, which is in complete conformity with the result of the audiometric test as per Table I (>15% prolonged recovery time).

Comparison of the data for the other exposures also shows that the maximum permissible exposure according to CHABA (Fig. 7) is lower than in the German diagram (Fig. 6). It can be seen, for instance, that with the German standard two rounds from the recoilless antitank weapon are easily permissible when, as in this case, using 30-dB hearing protectors, whereas with CHABA the limit of maximum stress is already reached with two rounds.

The values obtained from firing practice with an antitank weapon fitted with a subcaliber adaptor system can be dealt with in the same way. An exposure to 15 mortar rounds lies above the limiting line of both diagrams. Here the audiometric monitoring demonstrates that the damage-risk limit had been clearly exceeded because more than 8% of the gunners showed an extended recovery time and increased TTS.

The values entered in Fig. 6 have been determined by adding up the effective durations (C time). A multiple acoustic exposure is, of course, more dangerous in its effect on the ear than a single shot. The magnitude of the effect depends on the length of pauses between the individual shots. If the pause between shots is long enough, a larger number of rounds can be permitted, as our tests to determine the duration of pauses as a mitigating factor have shown during five-day firing practices with anti-tank weapons.

The relations between the recovery time, which in Germany is regarded as a yardstick, and the TTS_2 are represented in Fig. 8. These results concern additional firing practices, not represented in Table I. The subjects were different from those in Table I.

These tests justify the assumption that, if TTS_2 is high, recovery time is generally longer. The danger of a PTS grows with the magnitude of TTS_2. The larger variability, however, shows that, for precise tests, the recovery time has greater indicative value. Nevertheless, TTS_2 also provides an indication of acoustically endangered personnel and can therefore be considered, for example, as a test when assigning newly appointed personnel. For the practical assessment of the danger of a PTS, threshold measurements 24 h after firing are particularly useful.

SUMMARY

A comparative study of the CHABA damage-risk criteria for impulse noise and those of the Federal Republic of Germany (FRG) has been based upon the impulse diagrams of various weapons and a large number of audiometric tests before and after actual firing practice.

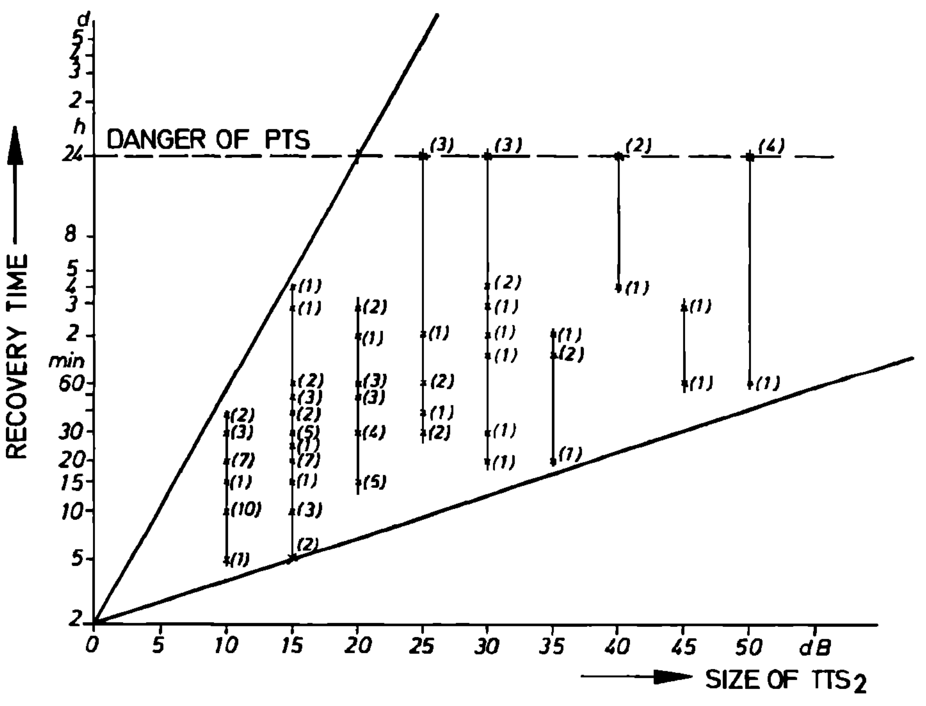

FIG. 8. TTS_2 (maximum measured at any frequency) in relation to time required for complete audiometric recovery, i.e., time required for TTS to reach 0 dB. Values are based on several firing practices in which a total of 477 soldiers participated. Of these, 374 showed no threshold shift after firing. For the other 103, the TTS_2 and associated recovery time are represented by the crosses; the number of soldiers is given in parentheses. The two diagonal lines indicate the total range of variability.

The comparison shows that CHABA's upper limits for tolerable exposure to impulse noise are lower than those for the FRG. The values given as the German limits are the result of numerous audiometric tests conducted in direct connection with systematic firing practice by the German army. Since the values are based upon more than 10000 such tests, we feel that their validity has been amply demonstrated.

The effects of repeated rounds of firing are determined from the peak pressure and the summation of effective durations. Owing to the usual pauses between rounds, in practice the number of rounds can be greater than would be allowed by summing the negative effects of individual rounds. In general, we have shown that the CHABA curve with its longer effective duration (B time) represents less auditory stress than does the German curve with its shorter effective duration (C time).

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