Z. Rechtsmedizin 73, 103—114 (1973)
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Originalarbeiten — Original Papers

Head Injuries Caused by Small-Calibre, High Velocity Bullets

An Experimental Study

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Received January 29, 1973

Summary. The effect of firearm calibre and bullet velocity on head wounds were studied in anaesthetized dogs. Autopsy, radiological and microscopic studies were undertaken. It was found that the injuries inflicted by 7.62 mm ammunition with an impact velocity of 714—798 m/sec were generally less severe than those inflicted by 5.56 mm ammunition with an impact velocity of 810 to approx. 1000 m/sec.

Effects of low velocity were observed when the 7.62 mm ammunition was used. Typical high velocity effects were noted with the 5.56 mm ammunition. The entrance wound generally corresponded to the size and shape of the projectile. The size of the exit wound was directly proportional to the projectile's impact velocity. Indirect (shock wave) damage to the cranium, brain and, in one case, the atlas was noted.

The effects of intra- and extra-cranial projectile fragments were studied together with severe pressure effects in 4 cases.

Model experiments were performed to study the pressure effects of the projectiles used. The maximum pressures measured were approximately proportional to the square of projectile velocities.

Zusammenfassung. Es werden experimentelle Untersuchungen über Kopfverletzungen, hervorgerufen durch Gewehrprojektile, an mit Pentobarbital betäubten Hunden beschrieben. Die Tiere wurden nach der Beschießung mit Munition verschiedenen Kalibers und Aufschlagsgeschwindigkeit röntgenologisch untersucht, die makroskopischen und mikroskopischen Befunde beschrieben. Es zeigte sich, daß die Verletzungen, die durch Geschosse von 7,62 mm-Kaliber und einer Aufschlagsgeschwindigkeit von 714—798 m/sec verursacht wurden, im allgemeinen weniger schwer sind als jene, die von 5,56 mm-kalibrigen Geschossen mit einer Aufschlagsgeschwindigkeit von 810 bis etwa 1000 m/sec herrühren.

Die beobachteten Verletzungen sind sowohl für Projektile niedriger wie hoher Aufschlagsgeschwindigkeit charakteristisch. Die Einschußwunden aller Munitionsarten entsprechen im allgemeinen in Durchmesser und Form denen der verwendeten Projektile. Der Durchmesser der Ausschußwunden nahm mit der Aufschlagsgeschwindigkeit des Projektils zu. Indirekte Verletzungen des Schädels, Gehirns und in 1 Fall des Atlaswirbels durch die Druckwelle des Geschosses wurden ebenfalls beobachtet.

In 4 Fällen fanden sich schwere, durch Druckwirkung von Projektilsplittern hervorgerufene Gewebszerstörungen.

In Modellversuchen wurde nachgewiesen, daß die entstehenden Maximaldrücke etwa dem Quadrat der Geschoßaufschlagsgeschwindigkeit proportional sind.

Key words: Head injuries by shooting — Firearm ammunition — Projectile velocity — Pressure effects of projectiles.

Introduction

The treatment of war injuries and the problems encountered in forensic medicine have stimulated research into the wounds caused by different kinds of projectiles.

The primary concern at present centres on the damage caused by small-calibre, high-velocity bullets, i.e. projectiles with a velocity of at least 750 m/sec (Rich, 1968). In contrast to low-velocity bullets, which produce more or less tubular wound passages of approximately the same size as the projectile's calibre high-velocity bullets with their higher kinetic energy produce a rapidly expanding wound passage with a diameter several times larger than that of the projectile. This ammunition also produces a particularly powerful pressure wave effect (cf. Troell *et al.*, 1969; Jernberg, 1971) and a tendency for the projectile to break into fragments (cf. Dimond and Rich, 1967; Rich, 1968; De Muth, 1969). The works of Finck (1965) and De Muth and Smith (1966), mainly dealing with injuries to the trunk and extremities, should also be mentioned among previous research into gunshot wounds caused by high-velocity ammunition.

No systematic, qualitative or quantitative studies of cranial injuries caused by high-velocity ammunition have yet been published, even though military interest has mainly involved this type of ammunition (cf. Westerhult, 1968). Previous investigations of gunshot wounds to the head have touched upon general neuropathological analyses without providing any information on the projectiles causing the injuries (Spatz, 1941; Campbell and Kuhlenbeck, 1950; Jacobs and Berg, 1970). An experimental study has indeed been published using X-ray flash films of the pulsating cavity produced in wounds inflicted by spherical, high-velocity projectiles (Butler *et al.*, 1945), but the anatomy of the wound was not analyzed. The present study concerns shooting experiments with anaesthetized dogs, head injuries being induced by high-velocity bullets fired at different ranges.

The purposes of the study were 1. to provide a general picture of the injury with respect to the pressure effect, lacerations, bleeding etc. in relation to the type and velocity of the projectile; 2. to study the remote effects of the pressure wave with respect to injuries corresponding to those described by Troell *et al.* (1960) in studies of other parts of the body; 3. to establish the incidence of projectile fragmentation with different types of ammunition (cf. Dimond and Rich, 1967; Rich, 1968; De Muth, 1969), and 4. to analyze size of entrance and exit wounds in the different cases and the extent to which these sizes relate to projectile velocity, a matter that is mainly pertinent to forensic medicine.

Ammunition, Range, Animals

Three different types of ammunition were used. Ammunition type 1 had a calibre of 7.62 mm and a muzzle velocity of 800 m/sec. Ammunition type 2 had a calibre of 5.56 mm and a muzzle velocity of 960 m/sec. Ammunition type 3 had a calibre of 5.56 mm and a muzzle velocity of 1090 m/sec. All the muzzle and impact velocities were obtained from the Defence Department Procurement Agency (FMV), where the velocities had been recorded with a chronograph. The impact energy (E) in each case was then calculated from the formula $E = \frac{mv^2}{2}$, where m = bullet mass, v = velocity, and g = accelaration due to gravity.

The type 1 projectile weighed 9.45 g and had a tombac-plated steel jacket. The thickness of the jacket was 0.65 mm at the nose, 0.60 mm at the middle and 0.55 mm at the base. The type 2 projectile weighed 3.50 g and had a tombac-plated jacket 0.35 mm thick at the nose, 0.40 mm thick at the middle and 0.50 mm thick at the base. The type 3 projectile weighed 2.77 g, and the jacket was 0.44 mm thick at the nose, 0.48 mm thick at the middle, and 0.50 mm thick at the base. Ammunition with a normal charge (types 1 a, 2 a and 3) and a calibre and velocity that are representative of high-velocity ammunition, was used as well as ammunition with a lighter charge (types 1 b and 2 b), the latter in order to obtain effects corresponding to firing at long ranges.

Normal type 1 a and 2 a ammunition at ranges of 2, 15 and 25 m and projectiles with lighter charges (types 1 b and 2 b) at the same ranges were used in two series, comprising 6 animals each, the latter providing an effect corresponding to shooting at ranges of 100, 115 and 125 m, respectively. Two shots were fired in immediate succession in one experiment in each series so as to induce multiple injuries, which are not uncommon. Ammunition type 3 was used on 2 animals, both at a range of 15 m.

Methods

7—18 months old beagles weighing from 11 to 15.5 kg and mongrel dogs of the same size and approximately same cranial shape, i.e. with a mesocephalic cranium, were used for the experiments. Beagles of this size have a brain volume of approx. 75 cc (Fox, 1970).

The animals were administered 10% pentobarbital intravenously until deep anaesthesia had been achieved, and various sites on the left side of the head perpendicular to the head's longitudinal axis were selected as targets for shooting. After the shooting (sacrifice by means of an intracardiac overdose of pentobarbital being necessary in only one case), an initial external examination was performed. The injuries were photographed, and radiograms were then made of the head. The brain was then perfused via the carotids with a 40% formaldehyde solution according to Lassek (1951), thereby facilitating fixation and removal of the brain. A post-mortem examination was performed on the heads, the cranial injuries were described and photographs were taken. In the subsequent brain autopsies, damage to the brain and its meninges was recorded, whereupon the brains were preserved in a 40% formaldehyde solution. Photographs supplemented descriptions at the autopsies, and samples were taken for microscopic examination in suitable cases. The samples were embedded in paraffin, cut into sections approx. 7 μ thick and stained with hematoxylin-eosin. Several of the sections obtained were photographed.

Model Experiments

In an attempt to illustrate the manner in which the shock pressure from a high-velocity projectile varies with projectile velocity, a series of experiments was conducted using the mechanical model reproduced in Fig. 11 a. The pressure pattern in this model was recorded 30 cm from the point of impact. In a living organism, this distance is sufficient to preclude the action of effects other than those caused by pressure variations, such as fragmentation effects. The model principally consisted of two identical rubber tubes (*1*) vertically suspended and fixed in relation to one another with wooden holders (*5*). The length of the rubber tubes was 75 cm, the internal diameter 50 mm and the wall thickness 3 mm. A thin-walled plastic tube (*2*), 50 mm in diameter and 30 cm long, was placed between and in close contact with the rubber tubes. The plastic tube constituted the target. All the tubes were closed at both ends and filled with bubblefree water. Model design was governed in part by difficulties in obtaining hits at an exact distance from the rubber tubes in which pressure measurements were made. Errors due to horizontal variations in the point of impact were largely eliminated, however, by taking the mean of the measured pressures in the two rubber tubes according to Fig. 11a. Pressures were recorded with piezo-electric pressure transducers (Atlantic Research Corporation, California, USA, type LC-10) mounted in special holders (*4*) made of plexiglass tube which were inserted in the upper ends of the rubber tubes. The transducers were connected to a type 555 Tektronix oscilloscope equipped with a Polaroid camera.

Results

Table 1 shows the results with regard to the wounding effects divided into 1. pressure wave effects, 2. projectile fragmentation, 3. contusions, 4. bleeding and 5. lacerations. This table shows that four sites for projectile passages were obtained: a) extra-cranial, b) frontal, c) occipital and d) central sites.

As expected, the extra-cranial hits caused the least damage. No changes in the brain or meninges were noted in one case (2b:2). However, there was contusion bleeding in the leptomeninx in another case (2a:1) (see Fig. 1).

Frontal and occipital shots produced relatively limited pressure wave effects (Fig. 2) and lacerations but sometimes significant meningeal bleeding (Fig. 3).

As expected, central hits produced the most severe pressure wave (Fig. 4) and laceration injuries (Fig. 5).

Direct shots into the neurocranium produced severe, fatal injuries, in all cases. The crania were shattered most extensively in cases 2a:2, 2a:3, 3:1 and 3:2. The pressure wave effect was so severe in the latter case that the atlas was also fractured (Fig. 6), and projectile fragments were found (Figs. 4 and 6). The most severe pressure wave effects were found in those cases in which fragments were observed. Fragmentation effects were demonstrated in one case (2b:3) despite

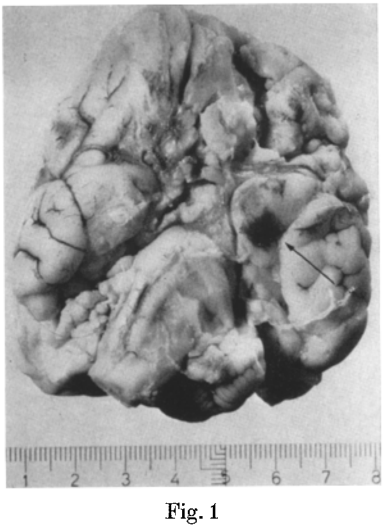

Fig. 1

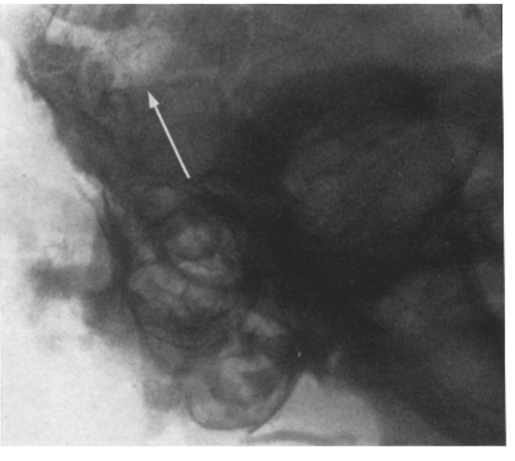

Fig. 2

Fig. 1. Ammunition type 2a. Contusion bleeding at the base of the left temporal lobe after an extracranial hit (arrow)

Fig. 2. Ammunition type 1a. Lateral, dextral radiograph. Occipital hit. Exit wound (arrow) with occipital fracture system

Table 1. Ammunition, range, injuries

Type of ammunition	Animal	Firing distance (m)	Impact		Site of		Morbid anatomy of wounds			
			velocity (m/sec)	energy (kpm)	injury	pressure wave effects	projectile fragmentation	contusions	haemorrhages	lacerations
1 a	1	2	798	307	occipital	occipital	—	—	central and around the wound	around the wound
	2	15	788	299	frontal	—	—	—	subdural	basal frontal
	3	25	780	293	frontal	frontal diastasis	—	—	subdural	frontal
1 b	1	2	731	257	occipital	occipital diastasis	—	—	ventricular	occipital
	2	15	722	251	central	skull cap diastasis, intra-cerebral splinters	—	contre-coup effects (of cerebellum)	subdural	around the wound
	3	25	714	246	occipital	occipital diastasis	—	—	right ventricular, and leptomeningeal	around the wound
2 a	1	2	957	166	superior part of the mandible	—	—	right temporal lobe	leptomeningeal	—
	2	15	942	161	central (2 entrance wounds)	general extensive diastasis	intra- and extra-cranial	—	left subdural	cerebral
	3	25	930	156	central and posterior part of the mandible	neurocranium	intra- and extra-cranial	—	extradural and subdural	the entire brain
2 b	1	2	837	127	frontal	extensive basal fractures	—	—	left subdural and in medulla oblongata	basal frontal
	2	15	822	122	extra-cranial	—	—	—	—	—
	3	25	810	119	frontal and demolition of the mandible (2 entrance wounds)	basal fractures	intra- and extra-cranial	parietal part of the left occipital lobe	basal leptomeningeal	—
3	1	15	1090[a]	168[b]	central	demolition of the neurocranium	intra-cranial	—	extra dural and subdural	the entire brain
	2	15	1090[a]	168[b]	central, and the posterior part of the mandible	general extensive diastasis	intra- and extra-cranial	—	extra dural and subdural	the entire brain

[a] Muzzle velocity. — [b] Energy.

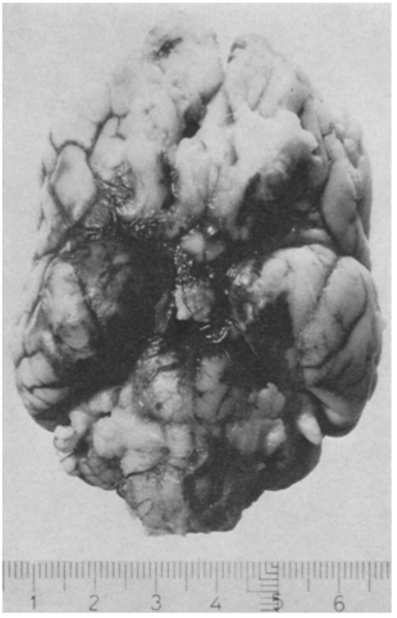

Fig. 3. Ammunition type 2 b. Extensive basal bleeding in the leptomeninx after a frontal and extra-cranial hit

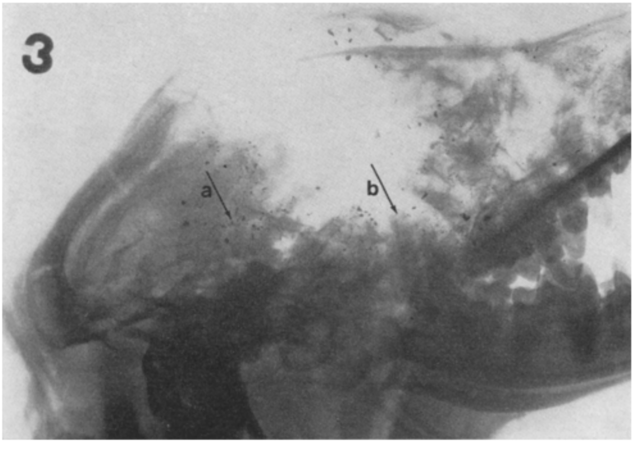

Fig. 4. Ammunition type 2 a. Central hit. The lateral, dextral radiograph shows demolition of the cranium and the posterior part of the right mandible. Multiple projectile fragments (*a*) and intra- and extra-cranial bone fragments (*b*)

the absence of pressure wave effects. In this case two shots had been fired in immediate succession, the projectiles smashing through the mandible first, and then the base of the skull. The projectiles were apparently demolished, despite a relatively low impact energy, due a) to the combination of their construction which, like type 3, featured a somewhat thinner jacket towards the nose, and b) the two-stage resistance from the skeleton.

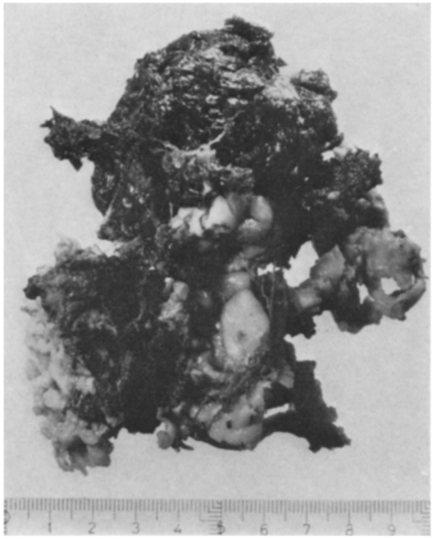

Fig. 5. Ammunition type 2a. Completely lacerated brain after a central hit

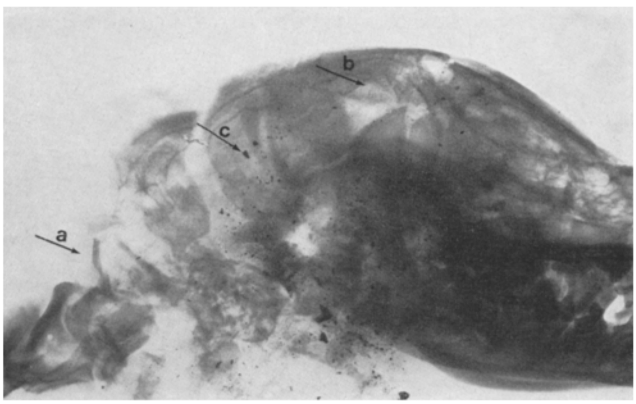

Fig. 6. Ammunition type 3. Lateral, dextral radiograph. Neurocranium demolished after a central hit. Wide occipital sutural diastasis. Posterior part of the mandible and the atlas (*a*) fractured. Abundant intra- and extra-cranial bone fragments (*b*) and metal fragments (*c*)

Injuries to the brain and its meninges appeared as contusion bleeding from extra- or intra-cranial traumata, as wound furrows or limited crushing and lacerations and as damage to almost the entire brain. In the cases reported here, 1 b : 1—3, displayed typical low-velocity effects with limited laceration around the wound passage (Fig. 7) (cf. Rich, 1968; Troell *et al.*, 1969), while typical high-velocity effects with severe laceration of the brain were noted in cases 2a:2, 3 (Fig. 5) and 3:1, 2 (cf. Rich, 1968; Troell *et al.*, 1969). From the neurosurgical point of view, the indirect (pressure wave) injuries occurring in most cases were of special

Fig. 7. Ammunition type 1 b. Oblique wound track with lacerations after an occipital hit. Extensive bleeding in the leptomeninx

interest. Thus, there was remote bleeding in the medulla oblongata in case 2 b : 1 after a frontal shot (Fig. 8 a and b).

The entrance wounds were consistently about the same size as the projectile diameter. Only one case displayed a somewhat larger entrance wound with a hint of fissuring, possibly because of irregularities in the projectile's shape. The exit wounds were smaller than or equal to the projectile diameter with ammunition type 1 b and somewhat larger with ammunition types 1 a and 2 b at the two longer ranges. A significant increase in the size of exit wounds was noted with ammunition type 2 b at the shortest range and with ammunition types 2 a and 3 at all ranges.

Fig. 9 shows the extent to which $\frac{A_{out}}{A_{in}}$ (in which A_{out} = the area of the exit wound and A_{in} = the area of the entrance wound) is related to projectile velocity. As a result of the often rather irregular shape of exit wounds, the area of entrance and exit wounds was chosen for purposes of comparison rather than wound diameters. The diagram in Fig. 9 shows that there is a threshold value at 850—900 m/sec under which wound tracks with relatively small, low-velocity type exit wounds are most common. But at greater velocities, wound tracks with large, high-velocity type exit wounds appear consistently. The relatively low quotient for $\frac{A_{out}}{A_{in}}$ at 1100 m/sec in Fig. 9 was probably due to the fact that the projectile in this case had passed both petrous portions of the temporal bones, thereby leading to a comparatively smaller exit wound. These pilot studies seem to suggest that exit wound size is related to projectile velocity.

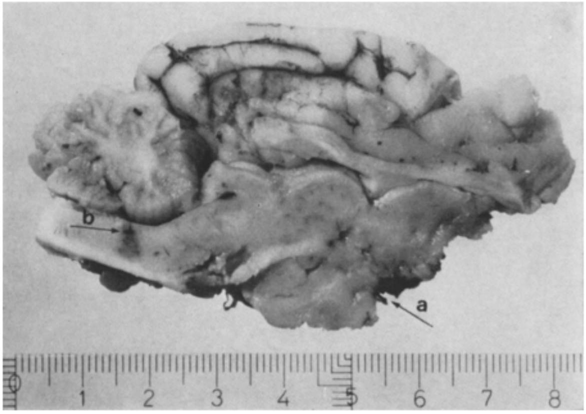

Fig. 8a. Ammunition type 2b. Sagittal section through the brain. Basal, frontal lacerationt with the wound track (*a*) and remote bleeding in the medulla oblongata (*b*) after a frontal his

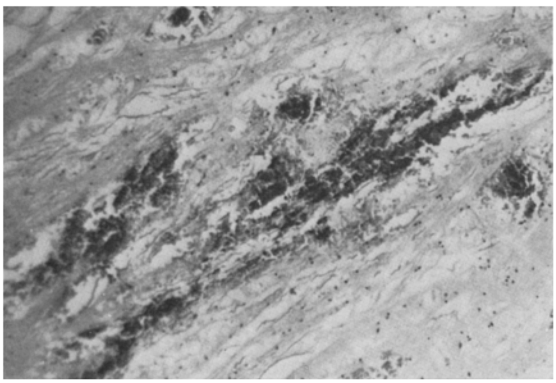

Fig. 8b. Microphotograph of the remote bleeding in picture 8a showing microscopic bleeding (H.-E. microphoto, 100×)

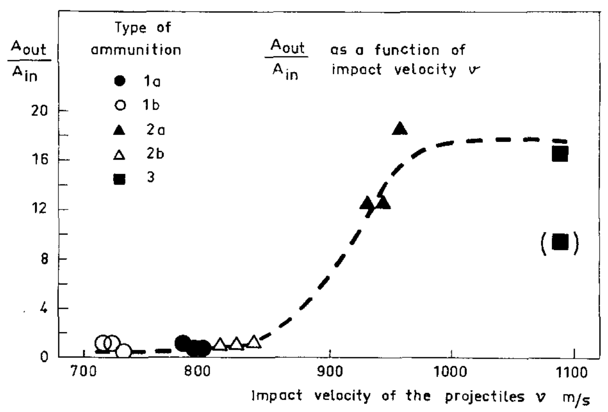

Fig. 9. $\frac{A_{out}}{A_{in}}$ in relation to projectile velocity. A_{out} = the area of the exit wound. A_{in} = the area of the entry wound

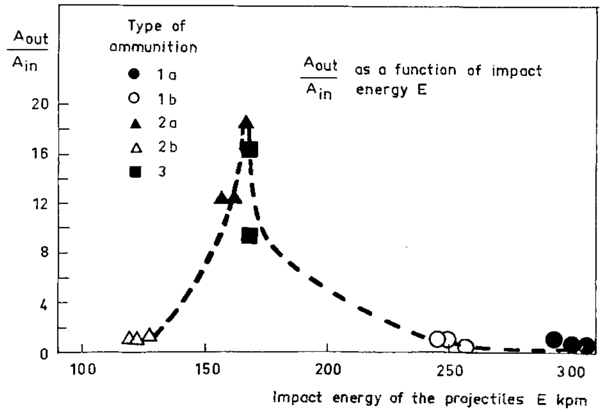

Fig. 10. $\frac{A_{out}}{A_{in}}$ in relation to the impact energy of the projectile

Model Experiments

The results of the model experiments, which should help to throw light on the propagation of pressure in tangential wounds, show (see Fig. 11b) that the maxi-

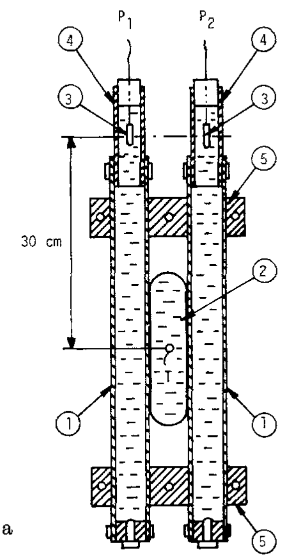

Fig. 11a

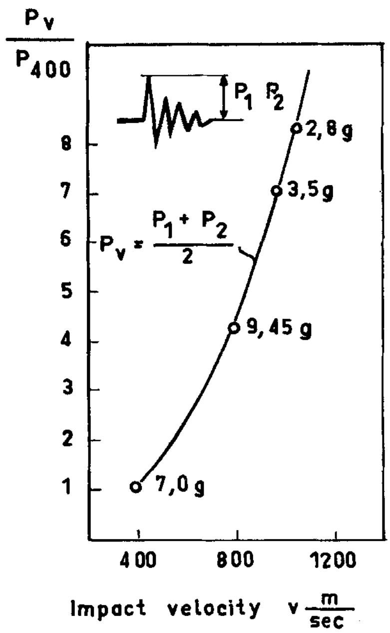

Fig. 11b

Fig. 11a. *1* rubber tube, *2* thin-walled plastic tube, *3* pressure transducer, *4* plexiglass tube, *5* wooden holder. *T* point of impact

Fig. 11b. Maximum pressure as a function of projectile velocity. P_1, P_2: Max. pressure recorded by gage 1 and gage 2 respectively. P_{400}: Max. pressure recorded at projectile velocity v = 400 m/sec. $\frac{P_{400}}{P_V}$: The ratio between max. pressure measured at projectile velocity v and pressure measured at a velocity of 400 m/sec. The projectile weight is stated for each measuring point mum pressures measured varied by approximately the square of the velocity of the projectile. The weight of the projectiles did not appear to be of any great significance in this case. The results of the model experiments suggest that the pressure wave effect and, accordingly, the damage caused by this in an organism is greatly dependent upon the velocity of the projectile causing the wound. This is especially applicable to damage so far from the wound track that primary laceration caused directly by the bullet is of little significance.

Discussion

It is evident from Fig. 10 that the high-velocity bullet with an impact energy of 150—200 kpm caused greater damage to the head than bullets with lower velocities and larger masses producing impact energies of 25—300 kpm.

In the present study dogs were chosen as the experimental animal because their heads display similarities to that of man. The cranial bones are relatively well-developed, and pneumatization of the cranium is generally the same as in the human skull. The pig was excluded as an alternative because its sinus frontalis extends very far to the rear as compared to the sinus of man.

One important difference between the head of the dog and that of man which must be considered in this context is the much greater mass of the temporal muscles in the dog. The reduction of the wounding effect which may be ascribed to this difference is probably compensated in man by the more heavily developed cranial bones, as also shown by the recorded wounding effects, which were in close agreement with those described by e.g. Spatz (1941).

Despite the limited number of experiments, certain facts have come to light in the present investigation which may be of neurosurgical interest. A brain contusion and fracture of the base of the skull caused by pressure wave effects from an extra-cranial hit were noted in one case. In facio-orbital hits by high-velocity projectiles, both fracture of the neurocranium and brain damage may arise, a circumstance which must be kept in mind when such injuries are treated. The severity of damage, even in intra-cranial hits, is determined primarily by projectile penetration together with the resultant pressure wave. Butler *et al.* (1945) clearly demonstrated the importance of the pulsating cavity in the development of skull injury by performing experiments involving the shooting at intact dog heads, in which severe pressure effects were obtained, and by shooting at dog crania only when there was no pressure effect. Another factor which further aggravates the injuries following cranial gunshot wounds is the penetration of bone fragments and, in some cases (at velocities around 1000 m/sec), even projectile fragments into the brain and its meninges. The latter effect probably arises because the jacket construction of the projectile used is not adequate for high velocities (cf. De Muth, 1969).

Acknowledgements. The authors wish to express their thanks to Lt. Col. H. Westerhult, Testing Division, FMV-A, VAB 1/i, Ursvik, and to Professor S. E. Olsson, The Royal Veterinary College, Mrs. B.-M. Svedenståhl, Mrs. U. Dahl and Mr. E. Arvebo, FOA 1, whose assistance was invaluable.

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