AN EXPERIMENTAL STUDY OF THE WOUNDING MECHANISM OF HIGH-VELOCITY MISSILES

BY

A. N. BLACK

B. DELISLE BURNS, M.R.C.S.

AND

S. ZUCKERMAN, D.Sc., M.R.C.S.

(For the Research and Experiments Department, Ministry of Home Security)

The fact that the amount of tissue destruction caused by small high-velocity bomb splinters may be out of all proportion to their size has been recognized for some time, and was the subject of correspondence in this *Journal* (1940, July 13 and 27). More obvious explanations of the disproportion between size of wound and size of missile—for example, that it is due to the irregular shape of the splinters and to their rotary movement (Wilson, 1940)—appear inadequate to explain the phenomenon, and it was therefore suggested (Zuckerman, 1940) that a more reasonable interpretation lies along the lines suggested by Cranz and Becker (1921) in their analysis of the effects of high-velocity missiles in soft media. If the physical explanations of Cranz and Becker are applicable to splinter wounds in flesh it would appear that the destructive effect of a small splinter is due to the motion imparted to the soft medium through which it passes, as a result of which the tissue is moved away violently from the track of the missile, an effect being produced similar to that of an internal explosion.

Observation also shows that splinters have little rotary effect in those media in which their effect has been studied. It has been found, too, that non-spinning projectiles fired from a smooth bore have an explosive effect in media such as mud (Cranz and Becker). It is thus improbable that the damage which occurs in the neighbourhood of the actual track of a splinter would be seriously altered by any peculiarities of shape or by any rotation. On the other hand, shape and rotation could undoubtedly have an effect on the track itself.

The experiments described in this paper have been designed to test this interpretation.

Method

The investigation was carried out on rabbits and on blocks of 20% and 5% gelatin. The former dilution was chosen as it corresponds to the dilution of protein in the body:

With the facilities available to us it proved impracticable to devise a splinter gun capable of firing irregular-shaped fragments of metal at high velocities in such a way that they could be accurately aimed. It was also impracticable to perform the experiments with model bombs. Accordingly a gun was devised (by Colonel P. Libessart of the Free French Forces) capable of firing, with a cordite charge, a 3/32-inch steel ball weighing 53 mg. at velocities varying between 500 and 5,000 f/s. The choice of this standard missile was to some extent arbitrary. In weight it corresponds to a very large proportion of the splinters which are shot off from any bomb or shell. It is possible, by means of relationships that have been worked out in other fields of ballistic study, to equate approximately some effects of the ball with those which would result from the penetration of any irregular-shaped splinter.

The velocity of each shot was measured by means of the Boys spark-photography method. The essential feature of this method is that the missile cuts a wire forming part of an electrical circuit, and thereby, through a relay, discharges a condenser across a spark gap. By using 10,000 volts enough light is obtained from an exposure of less than 1 microsecond to throw a shadow of the missile and target upon photographic paper. The impact and residual velocities of the missile are measured from the sound waves which are thrown off and which are photographed on the paper. By varying the interval between the impact of the missile on the target and the cutting of the wire, shadowgraphs of the target can be obtained at varying times after it is hit. Using identical targets for successive shots, it is thus possible to photograph the successive changes which take place in a target during the fraction of the second after it is struck. The present paper deals with such records.

Results

Blocks of gelatin 4 cm. by 4 cm. by 5 cm. were made by pouring a warm 20% solution of gelatin in water into moulds. Figs. 1 to 6 show silhouettes of the gelatin at varying times after the ball hit the front face of the block. Before each shot was fired control shadowgraphs were made, and these are outlined in each figure to give a measure of the distortion undergone by the gelatin block after its penetration by the ball. The magnification of the stages in each series of photographs varies; the dotted outline in each case, however, represents the same size of target. Unfortunately it was impossible to follow the cycle of changes through to the end because the blast of the gun, which follows behind the missile, forms a shadow that obliterates the gelatin block in the photograph. The blast actually helps to blow the gelatin block away. Each target was, however, recovered immediately after the shot was fired.

It will be seen that as soon as the ball enters the target a tail splash develops. This increases in size in the interval taken by the ball to traverse the block. As the ball emerges it pushes before it a head-cone which it ultimately leaves. This is the only distortion which occurs during the few microseconds taken by the ball to pass through the target. Immediately after complete perforation has been achieved, however, the block of gelatin undergoes considerable expansion, until it becomes some three to four times its original volume. In spite of this distortion the blocks return to their original size and shape. The only permanent visible effect of the shot is the small thread-like track made by the passage of the ball. This track is the same in appearance as that caused by pushing a needle through the block. Occasionally a few small bubbles of air and small radial fractures may be seen in the track. Experiments with similar blocks of 5% gelatin gave the same result.

A corresponding series of photographs were made of cylindrical 20% gelatin blocks shot diametrically. The changes demonstrated were the same as those shown by the rectangular blocks. In this series of observations shadowgraphs of the same target were made simultaneously in a plane at right angles to the usual plane of photography. This was done by reflecting, by means of a mirror, the light from the spark on to recording paper placed beneath the target. These additional shadowgraphs showed that the size of the target increases in all directions.

A third series of observations on identical cylindrical blocks of gelatin enclosed in a skin made of the inner tube of a bicycle tyre showed that the distortion for similar time-intervals after the first impact of the shot was considerably reduced, the reduction presumably being due to the resistance of the "skin" to the expansion of the gelatin.

Figs. 1 to 6 show shadowgraphs of rectangular gelatin blocks 4 cm. by 4 cm. by 5 cm. during and immediately after penetration by a 3/32-inch steel ball travelling at velocities between 700 and 1,000 m/s (2,296 and 3,280 f/s). In all the figures the dotted line shows the outline of a shadowgraph of the target immediately before shooting.

Fig. 7 shows the outline of the hind limb of an anaesthetized rabbit immediately before and a shadowgraph of

whole process occurring with explosive violence. In this way a central cavity, the pressure of which is presumably sub-atmospheric, is formed within the target. The peak of the change occurs after the missile has completely penetrated the target. It can be estimated from the series of tests on the 4 cm. by 4 cm. by 5 cm. gelatin blocks that 800 microseconds after impact the gelatin is distributed in a peripheral layer averaging about 0.5 cm. thick and surrounding

FIG. 1.—30 microseconds after impact. ($\times 0.70$)
Direction of shot $\longrightarrow$

FIG. 5.—840 microseconds after impact. ($\times 0.48$)
Direction of shot $\longrightarrow$

FIG. 2.—126 microseconds after impact. ($\times 0.68$)
Direction of shot $\longrightarrow$

FIG. 6.—860 microseconds after impact. ($\times 0.47$)
Direction of shot $\longrightarrow$

FIG. 3.—207 microseconds after impact. ($\times 0.64$)
Direction of shot $\longrightarrow$

FIG. 4.—300 microseconds after impact. ($\times 0.56$)
Direction of shot $\longrightarrow$

FIG. 7.—Shadowgraph of rabbit's hind limb taken 550 microseconds after impact. The 3/32-inch steel ball passed through the hamstring muscles. The impact velocity was within the same range as the previous shots. ($\times 0.56$)

$\longrightarrow$ Direction of shot.

the limb 550 microseconds after the impact of the steel ball. The limb shows the same type of distortion as the gelatin blocks. At the time of the shadowgraph the ball had completely traversed the limb.

Discussion

The changes which occur in the gelatin blocks can only be explained as being due to the formation of a cavity within the blocks with explosive violence. As the missile passes through the block it imparts motion to the particles in its track, and these fly off radially, imparting their momentum in turn to further particles (and so on), the

a central cavity approximately 5 cm. in diameter. The stresses imposed on the gelatin when struck must be great compared with those that it would be able to resist for a period longer than that in which the cycle of changes occurs. Nevertheless, it is surprising that there is so little evidence of damage in the gelatin blocks when the cycle of distortion is complete.

It has been shown experimentally that the cavitation caused in soft clay by high-velocity missiles is not due to the pressure of air drawn in behind the bullet (see Cranz and Becker). Thus there is no cavitation when a bullet is fired into a clay target down a prepared tubular track

with a diameter slightly greater than the calibre of the bullet. Furthermore, the explosive effect is also observed when a bullet is fired through a soft medium kept in a vacuum. But, on the other hand, the cavitation which occurs in a soft medium is almost certainly responsible for the drawing in of air, some of which may be pushed out again when the target returns to its previous shape. Air may be left in the track, as is shown by the subsequent presence of a few minute bubbles in the gelatin blocks. Small bubbles are also sometimes observed in splinter wounds in flesh.

The fact that the shadowgraphs of animal limbs are essentially similar to those of the gelatin blocks suggests that precisely the same changes occur in human or animal tissues that are traversed by high-velocity missiles. The distortion to which they are subjected can only be likened to that of an internal explosion, and at the height of the deformation, which occurs after the missile has left the part, the tissues must be stretched around a central cavity of relatively large dimensions. Under such conditions it is obvious that structures at great distances from the track of the projectile can suffer damage.

It is a common clinical observation, and one which we have confirmed experimentally, that minute puncture wounds, caused by small bomb splinters, in the skin on the entry and exit surfaces of a limb or other part of the body are often the only external signs of relatively serious internal injury. Our experiments with rubber-coated cylindrical blocks of gelatin provide a parallel to this observation in so far as only minute punctures are made in the rubber covering, in spite of the considerable immediate distortion of its contents. On the other hand, when the steel ball is fired at high velocity at the skinned limb of a dead rabbit or at a slab of meat a large crater is formed in the flesh on the entry side, and the destruction is much greater than in a corresponding part covered by skin.

The explosive character of the forces set up by the high-velocity ball in its passage is manifested not only by the amount of tissue destruction caused but also by the fact that we have often observed comminuted fractures of the femur of a rabbit even when the path of the projectile lay more than 1 cm. from the bone. These fractures can be explained by the fact that bone is relatively non-elastic, and that it fractures as a result of the stresses to which it is subjected by the explosive formation of the cavity along the path of the missile. In the same way we have found that heavy glass plates placed in contact with the gelatin targets, and at a distance of 2 cm. from the track of the ball, are shattered. It would be of interest to discover whether similar indirect fracturing of bone occurs in war casualties.

In contrast with bone, highly elastic structures such as arteries, veins, and nerves are apt to escape injury in wounds caused by high-velocity missiles. Thus post-mortem examination of exposed animals shows that larger vessels and nerves may run intact through regions in which muscle and smaller vessels are often much damaged. It is only rarely that we have observed relatively severe haemorrhage from larger arteries in wounds caused by the ball travelling at 2,500 f/s and upwards, whereas the impression so far gained in our work is that such haemorrhage is not uncommon in wounds caused by the ball when travelling at, for example, 1,500 f/s.

In further experiments we have found that a steel ball, travelling at a velocity of 2,400 f/s through a gelatin block in which is embedded an excised strip of artery containing fluid maintained at a pressure of 100 mm. Hg, will not rupture the vessel, in spite of the distortion of the block, except when the ball actually hits it.

Although larger nerve trunks appear to remain anatomically intact in high-velocity wounds, it should be remembered that they have momentarily undergone considerable stretching around the cavity caused by the missiles. This stretching may be a cause of the transient paralysis and analgesia which is sometimes said to occur as a result of bomb-splinter wounds, for it is known that a nerve can lose its conducting properties for some time after such distortion.

Summary

Experiments suggest that the disproportionate degree of tissue destruction caused by small high-velocity bomb splinters is due to the fact that particles lying in their path are thrown radially with sufficient violence to leave a central cavity around which tissues at some distance from the track are momentarily stretched. While blood vessels are usually elastic enough to experience this strain without anatomical and apparent functional injury, and nerves without obvious anatomical injury, bones are often broken at some distance from the track.

Our warmest thanks are due to Colonel P. Libessart, Free French Forces, whose design of the gun and assistance with the photographic technique made this work possible. We also wish to express our gratitude to Miss B. Hunt for her technical assistance.

REFERENCES

- Cranz, C. and Becker, K. (1921). *Handbook of Ballistics*, vol. 1. Translated from the 2nd German edition. H.M. Stationery Office.
Wilson, H. C. (1940). *British Medical Journal*, 2, 66.
Zuckerman, S. (1940). *Ibid.*, 2, 131.

BLOOD-PRESSURE-RAISING REFLEXES IN HYSTERICAL ANAESTHESIA

BY

J. VERNEY CABLE, M.D., M.R.C.P.

AND

F. H. SMIRK, M.D., F.R.C.P.

(From the Department of Medicine, University of New Zealand, Dunedin)

This paper is concerned with a study of two blood-pressure-raising reflexes in a case of hysterical anaesthesia. These are: (1) a reflex from skin described by Hines and Brown (1932), who showed that when the hand and forearm are plunged into water at 4° C. the blood pressure is raised reflexly as a result of the stimulus; (2) a reflex from muscle described by Alam and Smirk (1937), which depends on the fact that if ischaemic muscles are exercised the accumulation in them of metabolites leads reflexly to an increase of the blood pressure.

It was thought that it would be of interest to investigate a patient with hysterical anaesthesia by observing whether stimuli applied to an anaesthetic area gave rise to objective manifestations such as increase of the blood pressure. In the case described the skin was at first anaesthetic, later analgesic but not anaesthetic, and the muscle was hyperaesthetic.

The subject of our investigation was a married woman aged 35, with one child. There was a long history of various ill-defined abdominal complaints, which had been treated with little improvement by a number of gynaecological operations. The personal history revealed a background of much domestic friction, the patient having been twice married, and seemingly being little happier with the second husband than with the first. Following a domestic crisis she again became ill, and was admitted for investigation, when it was found that there was a complete cutaneous anaesthesia to pain, heat, and cold over the whole body surface supplied by spinal segments. The patient stated that she had been unaware of this condition until her attention was drawn to it during examination in hospital. There were no other signs to suggest any organic lesion of the nervous system. The Wassermann reaction was negative. Explanation to the patient