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Wound Ballistics: An Analysis of a Bullet in Gel

In a criminal investigation, it is often required to prove beyond all reasonable doubt that the wounds inflicted on the body of a victim could be caused by a particular firearm-cartridge combination fired under a specified set of circumstances. Such a situation occurred in the John F. Kennedy assassination case. During the Warren Commission Inquiry [*1*], a question arose as to whether the Mannlicher-Carcano rifle (recovered from the sixth floor of the Texas School Book Depository Building) and Western Cartridge Co. bullets and fragments (of the type recovered from Governor Connally's stretcher and in the Presidential limousine) were capable of causing the wounds inflicted on President Kennedy and Governor Connally. A scientific solution of this problem was obtained within the framework of wound ballistics by the scientists of the Wound Ballistics Branch of the U.S. Army Chemical Research and Development Laboratories at Edgewood Arsenal, Md.

It is obvious that a human body with its complex composition presents a most inhomogeneous material for study. However, for the purpose of studying its behavior under the impact of a missile, one can broadly consider it to be constituted of skin, bone, and soft tissues. Considerable effort [*2*] has been made in studying the behavior of skin, bone, and soft tissues under the impact of a projectile. Such studies have not only helped to establish the fundamental laws governing the motion of a missile in such media but have also helped in devising nonliving models for research and experimentation. Thus, 20% gelatin gel has been found to provide a suitable, homogeneous medium capable of duplicating the phenomena occurring in the soft tissues of a human body during the passage of a missile.

A review of the literature shows that comprehensive studies [*2*] on the various wound ballistics parameters have been made in the past, but these were mostly with respect to spherical projectiles. A modern small arms bullet is cylindro-conoidal in shape and is endowed with a high rate of spin. When such a bullet traverses a human body, the yaw makes a considerable difference and modifies the values of various parameters to a great extent. Only recently, DiMaio et al [*3*] have furnished energy loss data in 20% gelatin gel at 10°C (50°F) for a large number of handgun cartridges to compare their stopping rates. Whereas the data reported by DiMaio et al is a welcome addition to the existing literature, it is by no means complete inasmuch as the values of several other important wound ballistics parameters have not been reported.

It is desirable to collect data on as many wound ballistics parameters as possible even if they are correlated because it enables one to have a deeper insight into the factors

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governing the lethality of a missile. With this in view, the authors have undertaken a program of evaluating the various wound ballistics parameters in 20% gelatin gel for firearm-cartridge combinations commonly encountered in crimes in India and of correlating these data with the actual field performance as documented in the literature to judge the relative and absolute lethality of these combinations. A collection of these data for a large number of combinations may also enable a ballistician to establish parameters on the basis of which the lethality of a missile could be gaged with some confidence. To begin, investigations have been carried out with a .303, ball, MK7 bullet fired through a .303 service rifle. This was done because the nature of wounds caused by an MK7 bullet is well understood [*4*] because of its having been the service cartridge of British and Allied nations during the Second World War. Even after the war, it remained the service cartridge of several countries, including India, for many years. It is issued even now to the police forces in India and often figures in police firings. It has also found its way into the hands of antisocial elements and is thus frequently involved in criminal cases.

Materials and Methods

DiMaio et al [*3*] have argued that the penetration of a bullet beyond 6 in. (152 mm) is not important, because beyond this depth the bullet would have struck or bypassed the major organs or would have exited from the body. Further, from the point of view of incapacitation, the energy delivered to the vital organs such as brain, heart, lungs, and liver is important. In view of this, they have used 20% gelatin gel blocks at 10°C (50°F) having a length of 6 in. for energy loss studies. In the present investigation, blocks of 20% gelatin gel at 10°C and measuring 6 by 4 by 4 in. (152 by 102 by 102 mm) were used. The blocks provided a reasonable length (6 in.) in which the loss of bullet velocity could be measured without excessive bullet deviation due to the resistance offered by the gelatin gel and also without the bursting of the block because of expansion during the passage of an MK7 bullet.

A system of two electronic timers devised by one of us [*5*] was used to measure the striking and the remaining velocities for each single shot. The placement of the aluminum foil screens was such that the timers gave the mean striking velocity at a distance of 1.5 ft (457 mm) in front and the mean remaining velocity at a distance of 1 ft (305 mm) behind the gelatin gel block. The distance from the muzzle of the firearm to the front face of the block was 13 ft (4 m). This distance was sufficient for the bullet to overcome its initial wobble and to stabilize before striking the gelatin gel block.

Apart from the measurement of striking and remaining velocities, the volume of the permanent cavity left in the gelatin gel block was also measured with a buret filled with water and graduated to 0.05 cm^3 (0.003 $in.^3$) [*6*]. After the firing, the entrance hole was closed by finger, and the water was allowed to trickle into the cavity drop by drop through the exit hole until the cavity was full. The volume of water poured was calculated from the difference between the initial and the final readings of the water level in the buret. In cases where the cavity volume was low, an injection syringe [*6*] graduated to 0.025 cm^3 (0.0015 $in.^3$) was used to inject water into the cavity by pushing its needle inside the cavity as far as possible from the exit and slowly withdrawing it as the water was injected. In this way, fairly accurate measurements of the volume of cavity were obtained. The sizes of entrance and exit holes were also recorded, together with the loss of mass of the block. The latter was done in four of the ten shots by weighing the gelatin gel block before and after the firing on an open pan balance having an accuracy of ± 200 mg (±0.007 oz). The stability of the bullets after emerging from the gelatin gel block was inferred from the nature of the holes produced by it on thin paper screens.

Fired bullets were recovered in rolled absorbent cotton after passing through the gelatin gel block to ascertain whether the resistance of the block led to any fragmentation or distortion of the bullet. The firing was done with a .303 service rifle, No. 3, Serial No. ERA 693129, using .303, ball, MK7 cartridges manufactured in Kirkee Factory, India. In all, ten shots were fired and the data were collected for each single shot (Table 1). On the basis of these data, various wound ballistics parameters were calculated (Tables 2 and 3), and these were studied in relation to the lethal potentiality of an MK7 bullet.

Retardation Factor

The resistance experienced by a missile in 20% gelatin gel is proportional to the square of its velocity. This relationship holds down to fairly low velocities. At extremely low velocities, the viscous forces become predominant and the resistance varies as the first power of the missile's velocity. For the velocity range for which the square law of resistance holds, the retardation [2, pp. 120–122] experienced by a .303, ball, MK7 bullet can be expressed as

$$V\,(\mathrm{d}V/\mathrm{d}X) = -\alpha V^2 \qquad (1)$$

where V is the instantaneous velocity of the bullet after penetrating a distance X in the gelatin gel block and α is the retardation factor. If V and X are expressed in ft/s and ft, respectively, the units of α will be in ft^{-1}. Let V_S and V_R be the striking and the remaining velocities of the bullet on striking the gelatin gel block and after penetrating its full length (6 in. or 152 mm); then an integration of Eq 1 gives

$$\alpha = 2\,\log\,(V_S/V_R) \qquad (2)$$

Substituting for V_S and V_R from Table 1, one gets the values of α for each shot as shown in Table 3.

TABLE 1—*Data for each of the ten shots fired. All bullets were unstable on emergence from the gelatin block and were recovered without deformation.*

Shot	Striking Velocity V_S, ft/s	Remaining Velocity V_R, ft/s	Volume [a] of Permanent Cavity, in.^{3}	Size [b] of Hole, in.		Loss of Weight of Gelatin Block, g
				Entrance	Exit	
1	2382	2105	1.30	0.16(C)	2.00 × 1.40(E)	NA
2	2395	2165	0.67	0.12(C)	1.40 × 0.80(E)	NA
3	2259	1934	1.24	0.16(C)	2.00 × 1.20(E)	NA
4	2324	1938	1.56	0.16(C)	2.40 × 1.40(E)	NA
5	2525	2276	0.38	0.12(C)	1.00 × 0.32(E)	NA
6	2435	2181	0.77	0.16(C)	1.60 × 1.00(E)	4.5
7	2289	2068	0.18	0.16(C)	0.60 × 0.40(E)	1.7
8	2352	2114	0.69	0.16(C)	1.40 × 1.00(E)	3.6
9	2571	2424	0.13	0.16(C)	0.20 (C)	NA
10	2417	2016	1.35	0.16(C)	2.40 × 1.40(E)	12.0

C = circular, E = elongated, and NA = not accounted.

[a] This was originally measured in cm^3 and later converted to in.^{3}

[b] This was originally measured in mm and later converted to in.

TABLE 2—*Data on loss of velocity, loss of energy, and other measurements.*

Shot	Loss of Velocity, ft/s	Loss of Velocity, %	Initial Energy, ft·lb	Remaining Energy, ft·lb	Loss of Energy, ft·lb	Loss of Energy, %	Volume of Cavity per Unit Loss of Energy, in.^{3}/ft·lb
1	277	11.6	2160	1686	474	21.9	2.74×10^{-3}
2	230	9.6	2183	1784	399	18.3	1.68×10^{-3}
3	325	14.4	1942	1423	519	26.7	2.39×10^{-3}
4	386	16.6	2055	1429	626	30.4	2.49×10^{-3}
5	249	9.8	2427	1972	455	18.7	0.83×10^{-3}
6	254	10.4	2257	1811	446	19.8	1.73×10^{-3}
7	221	9.6	1994	1628	366	18.3	0.49×10^{-3}
8	238	10.1	2106	1701	405	19.2	1.70×10^{-3}
9	147	5.7	2516	2237	279	11.1	0.47×10^{-3}
10	401	16.6	2223	1547	676	30.4	2.00×10^{-3}
Mean	273	11.4	2186	1722	464	21.5	1.65×10^{-3}

TABLE 3—*Data on retardation factor, impulse, and related information.*

Shot	Retardation Factor α, ft^{-1}	Impulse I, lb·s	Pressure on Impact P, $lb/in.^2$	Time of Passage t, μs	Power Consumed, hp	Relative Yaw δ, deg	Diameter of Equivalent Cylindrical Cavity d, in.
1	0.247	0.216	14 400	224	3848	13.6	0.525
2	0.202	0.180	11 900	220	3298	11.0	0.377
3	0.310	0.254	16 300	240	3931	16.6	0.513
4	0.363	0.301	20 200	236	4822	18.7	0.575
5	0.207	0.194	13 600	209	3959	11.3	0.284
6	0.220	0.198	13 400	217	3736	12.1	0.404
7	0.203	0.173	10 900	230	2894	11.0	0.195
8	0.213	0.186	12 100	225	3273	11.7	0.382
9	0.118	0.115	8 000	200	2536	0	0.166
10	0.362	0.313	21 700	227	5414	18.7	0.535
Mean	0.244	0.213	14 250	223	3771	13.8	0.396

Loss of Velocity Energy

From the data in Table 1, the loss of velocity/energy as well as the percentage of loss of velocity/energy can be determined. This calculation is shown in Table 2 for each single shot.

Volume of Permanent Cavity for Unit Loss of Energy

Table 1 shows that the volume of permanent cavity left in the gelatin gel block as a result of the passage of an MK7 bullet varies from shot to shot. Its value ranges between 0.13 $in.^3$ (2.13 cm^3) and 1.56 $in.^3$ (25.57 cm^3) with an average of 0.83 $in.^3$ (13.85 cm^3). The loss of energy corresponding to the various shots has already been calculated and given in Table 2. One can thus determine the volume of permanent cavity left for unit loss of energy. This calculation is shown in Table 2.

Impulse Transmitted to the Block

The impulse of a force is defined as the change in linear momentum. Thus, the impulse I transmitted to the gelatin gel block during the passage of an MK7 bullet can be written as

$$I = (m/g)\ (V_S - V_R)\ \text{lb/s} \tag{3}$$

where m is the weight of an MK7 bullet (0.025 lb or 11.3 g) and g is the gravity (32 ft/s^2 or 9.7 m/s^2). The impulses corresponding to the ten shots are tabulated in Table 3.

Calculation of Relative Yaw

An examination of the permanent cavities in longitudinal section in the gelatin gel block revealed that the MK7 bullet had yawed during its passage through the block. The yawing motion of the bullet was also evident from the fact that the bullet on emerging from the block was unstable and produced keyholes on thin paper screens.

The size of exit was also, in general, much bigger than the entrance. The cavity volume was lowest for Shot 9 (0.13 in.^{3} or 2.13 cm^3) (see Table 1). The shape of this cavity in longitudinal section did not show evidence of any significant yaw. Although the bullet in this case was unstable on emerging from the gelatin block, the shape of the exit was circular and it was much smaller compared to that observed in the other nine shots. Hence, assuming this shot to be the one with zero yaw, one can estimate yaw in other shots relative to this shot. If $\alpha_{\min}$ is the value of α corresponding to this shot and α corresponds to any other shot where the yaw is α deg, then

$$\delta = 13\ [(\alpha/\alpha_{\min}) - 1]^{1/2} \tag{4}$$

This relationship is based on the fact that a yaw of δ deg increases the retardation factor [2, p. 131] by a factor of $1 + (\delta^2/169)$. Values of δ calculated from this formula are given in Table 3.

Pressure on Impact

When an MK7 bullet strikes a gelatin gel block, the pressure generated on impact can be calculated. If P is the pressure, A the area of presentation, and F the force opposing the motion of the bullet, then

$$\dot{P} = F/A = (m\alpha V^2)/(gA)$$

after substituting for F $[(mV)\ (\mathrm{d}V/\mathrm{d}X)]$ from Eq 1.

Taking $m = 0.025$ lb (11.3 g), $A = \pi r^2$ where $2r = 0.311$ in. (7.899 mm) for an MK7 bullet, $g = 32$ ft/s^2 (9.7 m/s^2), and α in ft^{-1} as in Table 3, then

$$P = (\alpha V^2/97.2)\ \mathrm{lb/in.}^2 \tag{5}$$

This formula can now be used to calculate the pressure for each shot as shown in Table 3.

Power Consumed

An idea of the power consumed during the passage of an MK7 bullet through the gelatin gel block can be had by calculating it for each single shot. Power is defined as the rate of doing work. Thus, if hp is the power in horse power,

$$hp = (E_L/t)\ (0.001818) \tag{6}$$

where E_L is the loss of energy in ft·lb given in Table 2 and t is the time, in seconds, taken by the bullet to traverse the gelatin gel block. An expression for t can be derived in terms of α, V_S, and V_R by rewriting the retardation as $\mathrm{D}V/\mathrm{d}t = -\alpha v^2$. On integrating, one gets

$$t = (1/\alpha)\ [(1/V_R) - (1/V_S)] \tag{7}$$

Values of t and hp are given in Table 3.

Diameter of Equivalent Cylindrical Permanent Cavity

The permanent cavity left by the MK7 bullet was in most cases far from cylindrical.

One can, however, imagine a cylindrical cavity having a length of 6 in. (152 mm) and equal in volume to the cavity formed in the gelatin gel block. If d is the diameter of this cavity in inches, ℓ the length of the gelatin gel block in inches, and v the volume of the permanent cavity in in.^{3} as tabulated in Table 1, then

$$d = \sqrt{(2v/3\pi)} \tag{8}$$

The calculation of d is shown in Table 3 for each of the ten shots.

Discussion

One of the important considerations in assessing the wounding power of a bullet is the efficiency with which it loses its kinetic energy while passing through a human body because it is this energy that ultimately goes into wound production. It is, therefore, obvious that the higher the loss of energy is, the greater the wounding effect of the bullet will be. In the present series of experiments, an MK7 bullet is found to lose, on an average, 464 ft·lb (631 J) of energy or 21.5% of its striking energy while passing through a 6-in. (152-mm) length of gelatin gel block. This figure is much greater than 58 ft·lb (79 J), which is considered to be the minimum to cause a disabling wound. If α is assumed to be constant over a wide range of velocities, it appears that for a striking energy of about 270 ft·lb (371 J), the loss of energy will be just 58 ft·lb. This striking energy corresponds to a striking velocity of about 852 ft/s (260 m/s) for an MK7 bullet.

For the ten-shot series, all the factors affecting α can be considered to be more or less constant except the velocity and the degree of yaw, because in no case was the bullet found to fragment or upset during its passage through the gelatin block. The difference in velocity was, of course, due to round to round variations. The bullet exhibited obvious yaw in all the shots except Shot 9. This yaw is expected because an MK7 bullet is a sharply pointed, heavy-base projectile.

Because of a tip of lightweight material such as aluminum, the center of gravity of the bullet is pushed further down towards the base, and because the center of gravity and the center of pressure do not coincide, an overturning couple operating on the lever between these two points results. The bullet is stabilized in air by imparting to it a high rate of spin. Whereas this spin is sufficient for air, it is completely inadequate for a dense medium such as gelatin gel or the soft tissues of human body. Therefore, as soon as an MK7 bullet enters the gelatin block, any initial yaw has a tendency to magnify and the bullet tumbles after penetrating a certain length of the gelatin block. This tumbling increases the area of presentation, resulting in an enhancement in the value of α and hence the resistance. An increased resistance leads to a more efficient dissipation of the bullet's kinetic energy, which increases its wounding effect. An examination of the values of α for the ten shots shows considerable variation over a range of 0.118 to 0.363 ft^{-1} with an average of 0.244 ft^{-1}.

The chief factor contributing to this variation is the degree of yaw, as explained above. This was confirmed by other observations. For example, an examination of a longitudinal section of the permanent cavity left in the gelatin gel block showed that the bullet track was straight and narrow up to a certain distance, after which it suddenly widened on account of the tumbling of the bullet. As the degree of yaw was different in different shots, permanent cavities of variable volume resulted. Table 1 shows that the volume of the permanent cavity varied between 0.13 in.^{3} and 1.56 in.^{3}, with an average of 0.83 in.^{3} Greater tumbling, in general, led to a permanent cavity of larger volume and greater loss of energy. On an average, for each ft·lb of energy doing work, a permanent cavity measuring 1.65×10^{-3} in.^{3} was left in the gelatin gel block.

The capacity of the gelatin gel block to make an MK7 bullet tumble was also evident from the nature of entrance, exit, and the holes on thin paper screens made by the bullet on emergence from the gelatin block. The bullet made a small circular entry having an average diameter of 0.15 in. (3.8 mm) into the gelatin block and an elongated exit much larger than the entry. In Shot 9, however, the entry and the exit were both circular and comparable in size (0.16 and 0.20 in., or 4.06 and 5.08 mm, respectively). The bullet invariably exhibited instability on emergence from the gelatin gel block. Although the permanent cavity formed in the gelatin gel block was in general far from cylindrical, one can imagine a cylindrical cavity equal in volume to the volume of the cavity and having a length equal to the length of the gelatin gel block (6 in. or 152 mm). The diameter of this equivalent cylindrical cavity has been calculated in Table 3 for each shot. It is found to vary between 0.166 and 0.575 in. (4.216 and 14.605 mm) with an average of 0.396 in. (9.46 mm), which is little greater than the average diameter of an MK7 bullet (0.311 in. or 7.88 mm).

An examination of the permanent cavities in longitudinal section further revealed that for Shot 9 the cavity was narrow, without any evidence of widening throughout its length. This showed that in this particular shot the bullet did not tumble to an appreciable extent and went straight, almost nose on, through the entire length of the block. The bullet, however, showed signs of instability on emergence from the block. Further, corresponding to this shot, the volume of the permanent cavity was exceptionally low (0.13 in.^3). The loss of energy was also lowest, being only 279 ft·lb, amounting to 11.1% of the striking energy. This shot is, therefore, clearly indicative of how important yaw is in wound production. Taking this shot as the one with zero yaw, one can attempt to estimate the yaw in the other nine shots on the basis that a yaw of δ deg increases the retardation factor by a factor of $1 + (\delta^2/169)$. Table 3 shows that the yaw for the rest of the nine shots varies between 11.0 and 18.7 deg, with an average of 13.8 deg.

It may be mentioned that the significance of yaw as brought out in the gelatin gel experiments is fully borne out by the field performance of an MK7 bullet. In this connection, it might be worthwhile to quote the following from Ref 7:

> Experience of wounds in the Great War has shown that as an effect of increased velocity, explosive wounds are seen up to ranges of 600 yards, and, as an effect of increased instability of the bullet after impact, all wounds show a higher degree of laceration of soft parts with finer comminution of bone, whether compact or cancellous.

Table 3 shows the calculation of the pressure generated on the impact of an MK7 bullet on a gelatin gel block. It is noted that the average pressure is 14 250 psi (97.25 MPa), which is much greater than the tensile strength of 20% gelatin gel at 10°C (50°F). Thus, the gel on the impact of an MK7 bullet will behave as if it had no strength at all. A marked splash is, therefore, likely to occur (as is seen in liquids), leading to loss of material from the entrance side in addition to that from the exit. That this splash does occur has been demonstrated by Beyer [2, p. 170] using high-speed motion picture photography. In the present series of experiments an attempt was made to evaluate this loss in four of the ten shots fired. The loss of material was sizeable, as tabulated in Table 1. It is also evident from Table 1 that the loss of material suffered by the gelatin gel block was smaller than that which would be calculated by multiplying the volume of the permanent cavity with the density of 20% gelatin gel at 10°C. This shows that the gel is inelastically compressed to a certain extent during the process of cavitation, thereby leaving a certain amount of residual permanent deformation.

Table 3 shows that an MK7 bullet, on an average, takes 223 μs to travel the entire length of the gelatin gel block (6 in.), and during this time it spends on an average 464 ft·lb of energy. This energy goes into wound production and consumes, on an average, 3771 hp (26 232 W). With such a high magnitude of power involved, the explosive wounds caused by an MK7 bullet become easily understandable.

Table 3 shows the calculation of impulse. Although it is not possible at the moment to interpret impulse in terms of the wounding power of an MK7 bullet, it may be possible to judge its importance when similar data for other cartridges is available for comparison and evaluation.

Within the framework of the experiments described in the present paper, it was possible to evaluate almost all the wound ballistics parameters. It was, however, not possible to study the formation of the temporary cavity because such study requires high-speed motion picture photography not available in the authors' laboratory. In spite of this, one can have an idea of this formation on the basis of certain well-established relationships [2, pp. 175 and 225]. For example, the volume of a temporary cavity is proportional to the energy delivered by the bullet. Further, the diameter of the temporary cavity is proportional to the square root of the space rate of change of bullet's energy. These relationships can guide us while comparing the lethal potentiality of bullets on the basis of gelatin gel data because the loss of energy as well as the space rate of change of bullet's energy are known from the data reported in the present paper. The importance of the temporary cavity cannot be underestimated as it is its expansion that results in wounds at locations remote from the bullet track, a characteristic of high-velocity missiles, including the MK7 bullet.

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