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Doppler radar velocity measurements for wound ballistics experiments

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Abstract Bullet velocity is a basic parameter in wound ballistics studies. It is usually measured electronically by means of a variety of solid or photoelectric barriers connected to equipment measuring the time elapsing between impulses, enabling the velocity to be calculated. With the advent of Doppler radar velocity measurement of large calibre artillery shells, the use of this equipment for wound ballistics experiments was investigated. Anaesthetized pigs were shot at a range of 9–10 metres and the velocities measured by Doppler radar and photocells were compared. A very good correspondence between the measured entry and exit velocities in low and medium velocity bullets was found, i.e. an average deviation of less than 1% (range 0–2%) between the two types of equipment. In high velocity bullets measurement of entry velocities was just as good, but in both methods measurement of the exit velocity was complicated by the cluttering of signals by fragments of tissue released from the exit wound and the deflection of the bullet, Doppler radar offers important benefits – simple set up, minimal risk of damage of equipment by stray bullets and very good accuracy – and may replace photocells and similar equipment in studies involving low and medium velocity bullets. Measurement of the exit velocity of high velocity bullets is unsatisfactory in both methods, and it is necessary to improve the Doppler radar method in order to measure that as well.

Key words Wound ballistics · Doppler radar · Velocity measurement

Zusammenfassung Die Geschoßgeschwindigkeit ist ein wichtiger Parameter ballistischer Studien. Üblicherweise basiert ihre Berechnung auf der Messung des Implusintervalls zwischen massiven oder fotoelektrischen Barrieren. Das bisher für die Geschwindigkeitsmessung von Artillerie-Granaten größeren Kalibers eingesetzte Doppler-Radar wurde für die Bestimmung der Ein- und Ausschußgeschwindingkeit bei wundballistischen Experimenten getestet. Es wurden Schüsse auf anästhesierte Schweine aus neun bis 10 Meter Entfernung abgegeben. Die Meßergebnisse der fotoelektrischen und der Doppler-Radarmethode wurden verglichen. Es ergab sich sehr gute Übereinstimmung der mit beiden Methoden gemessenen Geschwindigkeiten bei Untersuchungen von Geschossen niedriger und mittlerer Geschwindigkeit. Die mittlere Abweichung lag hier unter 1%. Übereinstimmung erhab sich auch bezüglich der Eintrittsgeschwindigkeit von Hochgeschwindigkeitsgeschossen. Erhebliche Abweichungen resultierten bei der Messung der Austrittsgeschwindingkeit von Hochgeschwindigkeitsgeschossen. Die Differenzen werden mit der Geschoßabweichung und durch die aus der Ausschußwunde herausgeschleuderte Gewebsfragmente erklärt. Vorteile der Doppler-Radarmessung gegenüber der fotoelektrischen Messung bei Untersuchungen von Geschossen niedriger und mittlerer Geschwindigkeit sind die sehr gute Präzision, die einfache Untersuchungsvorrichtung und das minimale Zerstörungsrisiko durch verirrte Geschosse. Die Geschwindigkeitsmessung von Hochgeschwindigkeitsgeschossen ist mit beiden Methoden unbefriedigend.

Schlüsselwörter Wundballistik · Doppler Radar · Geschwindingkeitsmessung

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Introduction

Bullet velocity has always been one of the fundamental parameters in wound ballistics (Sellier and Kneubuehl 1992). Solid barriers, high-speed photography, photocells and coils for measuring velocity have a number of practi-

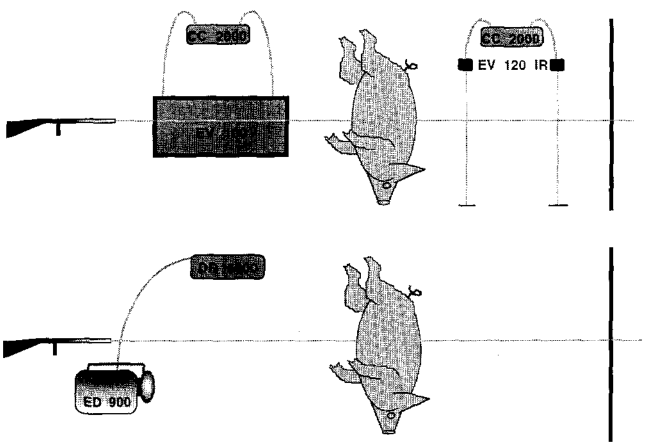


Fig. 1 Photocell (upper) and Doppler radar (lower) set-up compared, not to scale

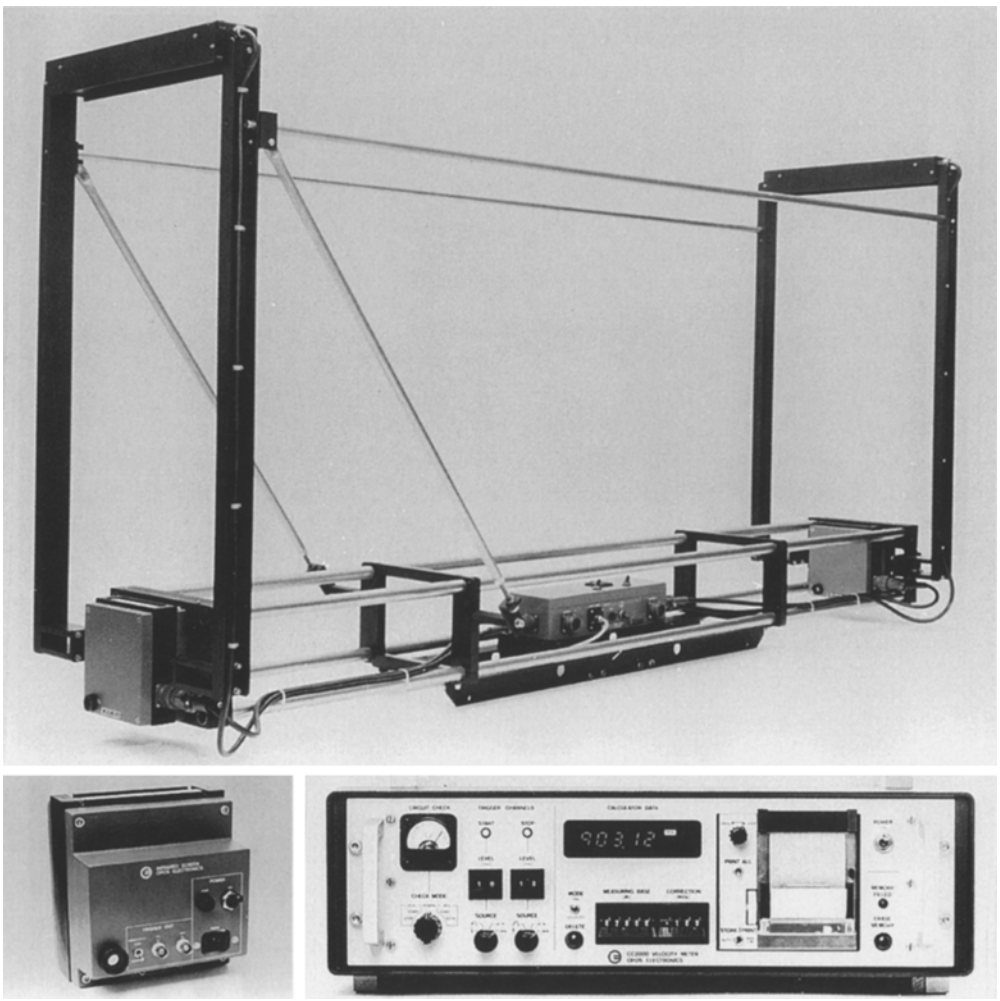
cal and theoretical disadvantages, accordingly a simpler, but equally precise method of measurement is desirable. Doppler radar has been used for a number of years to measure the velocity of artillery shells, but a refinement of the technique has meant that it is now possible to use it for small calibre bullets as well. In order to see whether this methodology can be used in wound ballistics, we used Doppler radar in connection with a set up which is similar to wound ballistics experiments with animals.

Materials and methods

The Defense Training Center (DMTC) has been staging exercises for a number of years where National Service doctors operate on anesthetized pigs during their reserve officers training course. The exercise has been described elsewhere and the details are not relevant in this investigation (Knudsen et al. 1990; Knudsen 1993). Briefly, the anaesthetized animals are suspended head down and shot with 3 different weapons. The animals are then taken through the normal chain of treatment and evacuation and are sacrificed at the end of the day. In order to be certain of the velocity of the bullets used, entry velocities are routinely measured and where exit velocities are of interest in conjunction with wound ballistic investigations these are measured as well.

The weapons used for this investigation were the SIG P210, a conventional 9 mm × 19 semiautomatic pistol, with a muzzle velocity of approx. 350 m/sec, the 5.45 mm × 39 AK-74 Kalashnikov assault rifle with a muzzle velocity of approx. 900 m/sec and a 7.62 mm M1 Carbine (US Carbine), which is a medium velocity weapon with a muzzle velocity of approx. 600 m/sec. The first 2 weapons were used to shoot the pig in the thighs while a shot in the

Fig. 2 Photocell equipment, EV 100 upper, CC2000 lower right, ER 120 IR lower left



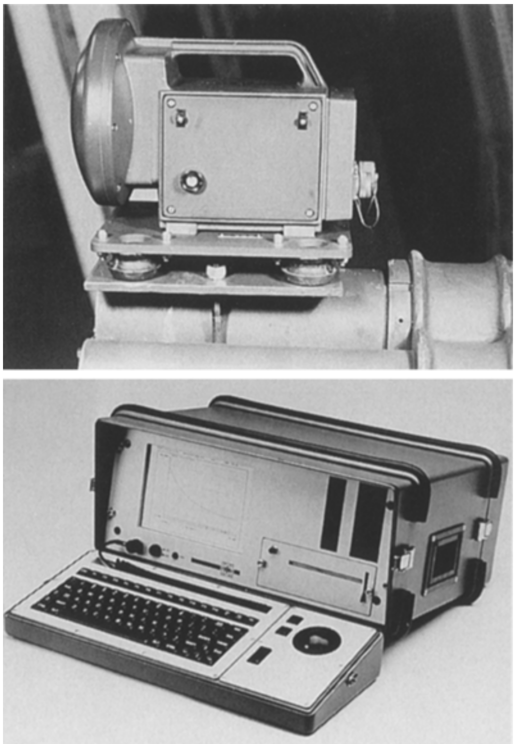


Fig. 3 Doppler radar equipment, ED900 (upper) and DR5000 (lower)

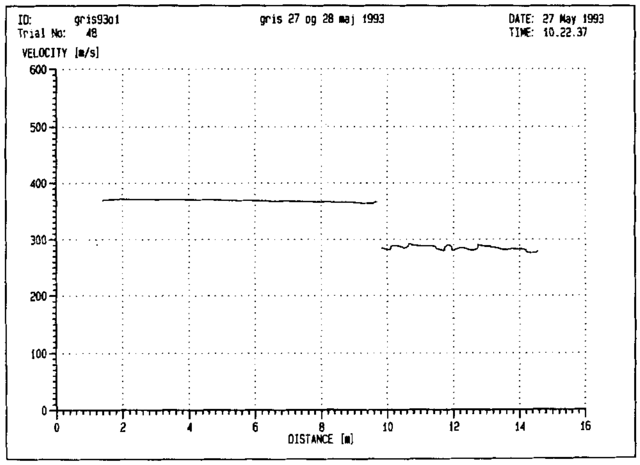


Fig. 4 Printout of P210

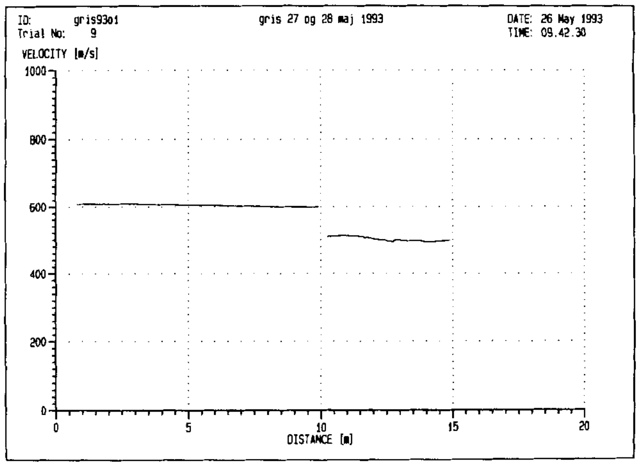


Fig. 5 Printout of US Carbine

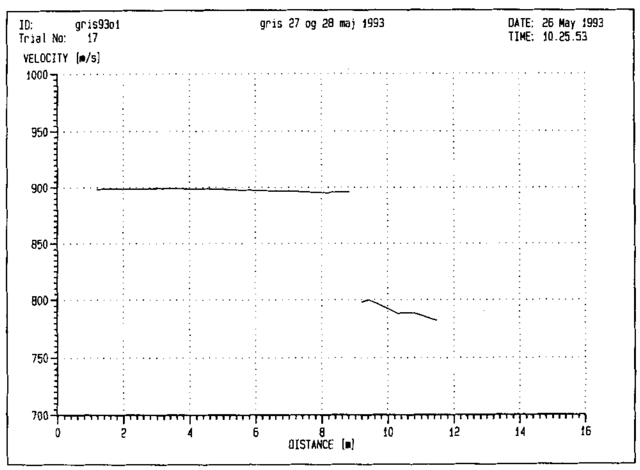


Fig. 6 Printout of AK-74

left side of the abdomen at the level of the phrenico-costal recess and the spleen was inflicted by the latter weapon. The ammunition used was full metal jacketed bullets of conventional design which is regularly supplied for the weapons.

Entry and exit velocities were initially measured by both photocells and Doppler radar, in order to confirm the accuracy of the entry velocity measurements; in later shots only the exit velocity was recorded by both methods (Fig. 1). Two sets of photocell equipment were used for measuring the velocities. Entry velocity was measured by an EV 100 Photocell Transducer System (mounted on a 2 m base) in connection with a CC2000 velocity meter, which measures the time between a start and a stop signal from the photocell transducers and then converts them into a velocity. The velocity is determined midway between the weapon and the suspended animal. Exit velocity was measured by two EV 120 IR Reflex Screens (mounted on a 2 m base) in connection with another CC2000 velocity meter. A witness screen was erected behind the Reflex Screens in order to be able to determine the deflection of the bullet when it had passed through the animal. Both systems described above are manufactured by TERMA Elektronik AS and conform to NATO STANAG 4114 "Measurements of Projectile Velocities" (Fig. 2).

As an alternative to photocells an "X-band Radar Antenna ED900" in connection with a "DR5000 Trajectory Analyzing System" was used (Fig. 3). The antenna was placed just below the muzzle of the weapon in order to minimize the angle between the trajectory of the bullet and the direction of the radar beam. The DR5000 Trajectory Analyzing System converts the signal from the antenna into a "velocity versus time registration" based on the Doppler-Radar-Principle. This registration is converted into a curve showing the "velocity versus distance". From this curve it is possible to determine both entry and exit velocities (Figs. 4–6). The distance between the weapon and the suspended animal was approximately 9 m, which corresponded well to the curves. This equipment is also manufactured by TERMA Elektronik AS and will – very soon – conform to NATO STANAG 4114. The witness screen was retained in situ for the Doppler radar experiments.

The results are only comparable with certain modifications. The photocells measure an average velocity over a distance of 2 m for both the entry and the exit velocity. The Doppler radar measures the velocity continuously. The entry velocity measured by the photocells is the average velocity over the distance between the photocells extrapolated to the front surface of the pig, while the Doppler radar measures the velocity just before the bullet hits the animal.

Likewise behind the animal the photocells measure the average velocities between them extrapolated to the back of the pig while the Doppler radar measures the bullet as it emerges from the body.

Results

In the case of the entry velocity, 11 shots with the P 210, 9 shots from the US carbine and 9 shots from the AK-47 provided results by both photocells and Doppler radar. In the case of the exit velocity 13 shots with the P 210, 9 shots from the US carbine and 4 shots from the AK-47 provided results. The accuracy of the velocity measurement with the Doppler radar is normally better than 0.1%. Because of the yaw of the projectile after it has passed through the pig, the centre for the radar cross section "electronically" move forward and backward and therefore, the accuracy of the exit velocity measured with the Doppler radar is decreased approximately tenfold, but is still better than 1%. The results from the 2 methods are compared in Tables 1–6.

Table 1 Entry velocities with the P210

P210	$Entry_{(P)}$ (m/s)	$Entry_{(D)}$ (m/s)	$Entry_{(P)} - Entry_{(D)}$ (m/s)
1– 1	360	356	+4
1– 2	360	359	+1
1– 3	345	345	0
1– 4	347	343	+4
1– 5	360	359	+3
1– 6	354	351	+3
1– 7	352	351	+1
1– 8	357	352	+5
1– 9	357	356	+1
1–10	361	358	+3
1–11	340	336	+4

Table 2 Exit velocities with the P210

P210	$Exit_{(P)}$ (m/s)	$Exit_{(D)}$ (m/s)	$Exit_{(P)} - Exit_{(D)}$ (m/s)	Deflection
2– 1	318	318	0	3°
2– 2	293	290	+3	18°
2– 3	286	284	+2	1°
2– 4	290	287	+3	4°
2– 5	287	283	+4	3°
2– 6	306	304	+2	3°
2– 7	296	294	+2	6°
2– 8	255	262	–7	6°
2– 9	269	274	–5	3°
2–10	259	256	+3	6°
2–11	287	279	+8	3°
2–12	255	250	+5	5°
2–13	270	263	+7	1°

Table 3 Entry velocities with the US Carbine

US Carbine	$Entry_{(P)}$ (m/s)	$Entry_{(D)}$ (m/s)	$Entry_{(P)} - Entry_{(D)}$ (m/s)
3–1	580	578	+2
3–2	583	579	+4
3–3	586	585	+1
3–4	588	588	0
3–5	588	587	+1
3–6	581	580	+1
3–7	594	593	+1
3–8	591	589	+2
3–9	580	578	+2

Table 4 Exit velocities with the US Carbine

US Carbine	$Exit_{(P)}$ (m/s)	$Exit_{(D)}$ (m/s)	$Exit_{(P)} - Exit_{(D)}$ (m/s)	Deflection
4–1	437	435	+2	7°
4–2	516	517	–1	1°
4–3	439	440	–1	6°
4–4	412	409	+3	11°
4–5	423	425	–2	8°
4–6	469	469	0	2°
4–7	414	418	–4	5°
4–8	510	511	–1	4°
4–9	492	494	–2	4°

Table 5 Entry velocities with the AK-74

AK-74	$Entry_{(P)}$ (m/s)	$Entry_{(D)}$ (m/s)	$Entry_{(P)} - Entry_{(D)}$ (m/s)
5–1	898	898	0
5–2	901	898	+3
5–3	894	889	+5
5–4	892	890	+2
5–5	903	903	0
5–6	892	891	+1
5–7	895	892	+3
5–8	896	896	0
5–9	896	896	0

Table 6 Exit velocities with the AK-74

AK-74	$Exit_{(P)}$ (m/s)	$Exit_{(D)}$ (m/s)	$Exit_{(P)} - Exit_{(D)}$ (m/s)	Deflection
6–1	560	725	–165	5°
6–2	509	495	+14	5°
6–3	590	673	–83	0°
6–4	634	698	–64	18°

Discussion

A number of different techniques have been used to establish the entry and exit velocities of bullets. Metal or other solid foils (Berlin et al. 1976; Fackler et al. 1986, 1988; Fackler and Malinowski 1988; Harvey et al. 1962; Hopkins and Watts 1963; Nordstrand et al. 1979; Tikka et al. 1982), wire grids (Berlin et al. 1979; Rybeck 1974;

Suneson et al. 1989) or photocells (Giles and Leeming 1989; Kundsen 1988, 1993; Knudsen et al. 1990; Nordstrand et al. 1979; Tikka et al. 1982) create a barrier which when broken will enable the velocity to be measured by means of electrical equipment. In other methods a bullet made of a magnetic material passing through a coil will induce changes in the current, which enables the velocity to be determined (Sellier and Kneubuehl 1992), high-speed photography triggered by the bullet may be used (Sellier 1967) or one may photograph sound waves in air as the bullet passes a row of small holes (Harvey et al. 1962). Photocells have succeeded most of the other methods which create a barrier for the bullet and are now the standard method of measuring bullet velocity, both at entry and exit. The most precise measurements of the entry velocity are obtained by measuring as close to the target as possible. The closer the photocell is placed to the target and thereby the further from the muzzle, the greater are the demands put upon the accuracy of the shooter. There is a very real risk of hitting the photocell itself with a stray bullet. There will frequently be a physical limitation to the minimal distance from the photocell to the animal. Therefore the velocity measured is not only an average over the length of the photocells, it is also not measured at the entry, but at a distance from this. This problem is of less or no importance when immobile simulants like gelatine, soap or cadavers are used. We very often see a deviation of the bullet after hitting the target (up to 18° in the cases used here), which means that the use of a photocell like the one in front of animals is impractical behind the target. Instead so-called screens are used. These are placed at an even longer distance from the animal and will furthermore measure the bullet travelling at an angle to the ideal trajectory between the 2 sky screens, a problem which is shared by the Doppler radar measurement. In order to get a reliable measurement of velocity, the distance between the 2 photocells has to be determined with an accuracy of 0.1 mm.

Doppler radar, which has been used for many years to measure the velocity of artillery shells, should theoretically be adaptable to small arms as well, and a refinement of the technique has made this possible (Sørensen and Lolck 1992).

Since the only equipment used in the shooting gallery or range is the antenna which is placed ideally as close to the muzzle as possible, accordingly the risk of hitting the equipment is, to all intents and purposes, non-existent.

Our results showed close agreement between the measurements of the velocity of the bullet both before and after hitting the target. The average deviation was less than 1% (range 0–2%) for the entry velocity. The fact that the deviation was independent of the velocity indicates that this deviation is the tolerance inherent in the measurements. As for the exit velocity a similar situation exists for the low and medium velocity bullets – an average deviation of less than 2% (range 0–3%) – but for the high velocity bullets measurements of the exit velocity were unsatisfactory in both methods.

By itself the ease of measuring the entry velocities would justify its use, but also the more complicated behind-the-target measurement was successful, although there were difficulties in the case of the AK-74. Our choice of this rifle, as representative of high velocity weapons, was one of expediency – it has been used for this exercise for several years – and for good theoretical reasons as well, which are the same as those that have caused the DMTC to use it in the exercise. It is characterized by having a very high muzzle velocity and the bullet will not fragment in the target (Fackler et al. 1984; Knudsen 1993). In most cases this bullet will dilacerate the skin at the exit wound, producing many pieces of tissue which clutter the radar signal, resulting in a very considerable variation in the exit velocities measured. As can be seen, the exit velocity varied from 509 m/sec to 634 m/sec measured with photocells and from 495 m/sec to 725 m/sec when measured with Doppler radar. The conclusion must be that measurement of exit velocity of the AK-74 is difficult, no matter what method is used, and a further refinement of both methods is called for. A solution using Doppler radar where the distance available for recording the velocity behind the pig is extended to a degree whereby the bullet has manifested itself by its longer range and better maintained speed as compared to the tissue fragments, is complicated by the necessity for a very large witness screen to record the deflection. The size of such a screen would probably be prohibitive. Another solution using a foil to act as a "mirror" facing the exit wound is being studied. A further aspect of the AK-74, and the one responsible for the few recorded shots, is the often extreme deflection of the bullet, where angles up to 45° were observed.

It is of course not possible to measure energy deposit by measuring entry and exit velocities of a fragmenting bullet like the one used in the M16 rifle. Until further advances are made, a ballistic pendulum, which may be used to measure energy deposit with fragmenting bullets, would seem necessary if energy deposit using the AK-74 is to be measured reliably (Nordstrand et al. 1979; Janzon et al. 1979).

The Doppler radar measures the exact velocity of the exiting bullet if there is no angle between the ideal and actual trajectory, but will be less and less precise as the angle increases. This problem is shared by photocells and is in practice solved by manually measuring the deflection. The exact velocity can then easily be found.

The biggest disadvantage of the Doppler radar is the price of the eqiupment. Both antenna and data processing equipment, hardware and software are significantly more expensive than traditional photocell equipment. The ED900 and the DR5000 have been used since they became available, but represent a kind of "overkill" and cost 5 times as much as the photocell set-up. A tailor-made antenna and velocity analyzer would only cost twice as much as photocells, and convenience in use and minimal risk of damage from bullets easily justify the extra expense. On the other hand the equipment used allows one to study the behaviour of the bullet in flight, e.g. the yaw of the bullet, and a study of this phenomenon is being undertaken. The Doppler radar technique affords an improvement upon the previously used photocell measurements on almost all counts, it is considerably more expensive, but where available it may replace photocells in the future.

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References

Berlin R, Gelin LE, Janzon B, Lewis DH, Rybeck B, Sandegård J, Seeman T (1976) Local effects of assult rifle bullets in live tissues. Acta Chir Scand Suppl 459:1–76

Berlin R, Janzon R, Rybeck B, Seeman T (1979) Retardation of spherical missiles in live tissue. Acta Chir Scand Suppl 489: 91–100

Fackler ML, Malinowski JA (1988) Internal deformation of the AK-74; A possible cause for its erratic path in tissue. J Trauma 28 Suppl: S72–S75

Fackler ML, Surinchak JS, Malinowski JA, Bowen RE (1984) Wounding potential of the Russian AK-74 assault rifle. J Trauma 24:263–266

Fackler ML, Bellamy RF, Malinowski JA (1986) Wounding mechanism of projectiles striking at more than 1.5 km/sec. J Trauma 26:250–254

Fackler ML, Bellamy RF, Malinowski JA (1988) A reconsideration of the wounding mechanism of very high velocity projectiles – Importance of projectile shape. J Trauma 28 Suppl: S63–S67

Giles MJ, Leeming DW (1989) An aerodynamic model for unstable projectiles. Proceedings 11th International Symposium on Ballistics, Vol I, Bruxelles, pp. 685–694

Harvey EN, McMillen JH, Butler EG, Puckett WO (1962) Mechanism of wounding. In: Coates JB, Beyer JC (eds) Wound Ballistics. Office of Surgeon General, Department of the Army Washington DC, pp 143–235

Hopkinson DAW, Watts JC (1963) Studies in experimental injuries of skeletal muscle. Proc R Soc Med 56:461–468

Janzon B, Berlin R, Nordstrand I (1979) Drag and tumbling behaviour of small calibre projectiles in tissue simulant. Acta Chir Scand Suppl 489:57–70

Knudsen PJT (1988) The effect of the THV bullet in animal tissue. Z Rechtsmed 101:219–227

Knudsen PJT (1993) Cytology in ballistics. An experimental investigation of tissue fragments on full metal jacketed bullets using routine cytologic techniques. Int J Leg Med 106:15–18

Knudsen PJT, Høier-Madsen K, Darre E (1990) The effect of decontaminant ("dutch powder") in experimental wounds. Med Corps Int 5:26–27

Nordstrand I, Janzon B, Rybeck B (1979) Break-up behaviour of some small calibre projectiles when penetrating a dense medium. Acta Chir Scand Suppl 489:81–90

Rybeck B (1974) Missile wounding and hemodynamic effects of energy absorption. Acta Chir Scand Suppl 450:1–32

Sellier K (1967) Schussentfernungsbestimmung. Schmidt-Römhild, Lübeck, pp 17–19

Sellier K, Kneubuehl BP (1992) Wundballistik und ihre ballistischen Grundlagen. Springer Berlin Heidelberg New York, pp 30–33

Sørensen OH, Lolck J-E (1992) Testing light-weight aramid-based ballistic protection materials by means of a Doppler Radar. Proceedings Ballistics 1992 13th International Symposium, Stockholm, Vol III, pp 171–177

Suneson A, Hansson H-A, Lycke E, Seeman T (1989) Pressure wave injuries to rat dorsal root ganglion cells in culture caused by high-energy missiles. J Trauma 29:10–18

Tikka S, Cederberg A, Levänen J, Lötjönen V, Rokkanen P (1982) Local effects of three standard assault rifle projectiles in live tissue. Acta Chir Scand Suppl 508:61–77