INFECTION IN MISSILE WOUNDS

Gordon-Watson Lecture delivered at the Royal College of Surgeons of England on 12th October 1967 by

Brigadier J. M. Matheson, O.B.E., M.D., F.R.C.S.
Consulting Surgeon to the British Army of the Rhine

Introduction

SIR CHARLES GORDON-WATSON (Fig. 1), whom this lecture commemorates, was one of the leading British surgeons in the first half of this century. An account of his life and work was the subject of the first Gordon-Watson Lecture (Norbury, 1960) and to those who knew the man it was

Fig. 1. Sir Charles Gordon-Watson.

a touching tribute born of affectionate observation and an harmonious association. He was a cultured man of deep religious conviction and a wide range of interests; an ideal background for his outstanding surgical talents. His was another of the famous names of surgeons who had served on the staff of St. Bartholomew's and St. Mark's Hospitals and who had rendered distinguished service to this College as a member of its Council for some 15 years and as its Vice-President from 1935 to 1937.

The Army Medical Service also recalls with pride the loyal and distinguished service rendered by Sir Charles Gordon-Watson in three wars. During the South African War (1899–1901) he served with the Army as civil surgeon. His outstanding experience was in the Great War of 1914–18, when he became Colonel and Consulting Surgeon to the Second Army in France and later to the British Force in Italy. For his work

he was the recipient of many honours culminating in 1919 with the bestowal of a knighthood. He was 65 when the Second World War broke out and, at a time when most men deserved a rest from their labours, he was among the first to offer his services to his country. As a Major-General and Consulting Surgeon to the Army at home from 1939 to 1942 his unique experience and wise counsel were invaluable in the building up of the Army surgical organization in those early war years.

I have chosen as the subject of my commemorative address that of infection in missile wounds with a special reference to gas gangrene. It was a problem of considerable magnitude to first World War surgeons, among them Sir Charles Gordon-Watson. I shall consider the principles of prevention and treatment which were established then and, by surveying the advances since, I hope to show that the principles still hold good and that the hazard of missile wound infection continues to be a challenge.

Theories of infection and Lister

Infection has complicated war wounds since time immemorial, and more so since the introduction of gunpowder in the 13th century. The cause of wound infection had been the subject of much speculation, being variously attributed in the middle ages to specific poisons and to the presence of foreign bodies and damaged tissue. That germs might cause infection had already been mooted in the 16th century, but little had emerged to develop the theory. As late as the 19th century putrefaction of surgical wounds was still a common and appallingly lethal occurrence and was attributed to the action of oxygen on exposed tissues and to chemical ferments. Microbes were assumed to be the *result* of the oxidative process.

Undoubtedly difficulties of communication, scepticism and bigotry hindered any co-ordinated progress towards the explanation and control of wound infection. Poynter (1967) has reminded us of several events: an Italian, Bassi, in 1835, had established that a fungus caused an infective disease of silkworms. In 1840 a German pathologist, Jacob Henle, had propounded a germ theory for the causation of disease. In 1847 Semmelweiss had reduced the incidence of puerperal fever in his obstetric wards by the simple expedient of scrupulous hand-washing among his staff. In France, in 1850, Davaine had identified the anthrax bacillus in the post-mortem blood of an infected sheep. In 1862, a Manchester surgeon, Edward Lund, had reported favourably on the use of carbolic acid in the treatment of open wounds. All these had remained relatively isolated achievements and the breakthrough only came when Dr. Thomas Anderson of Glasgow fired Lister's imagination when he told him of Louis Pasteur's work, published in 1863, attributing putrefaction and fermentation to microbes which could be airborne. Lister (Fig. 2) had been grappling for a number of years with the scourge of hospital sepsis on the inspired assumption that the disease was caused by germs in the air.

Ignoring contemporary scepticism and controversy surrounding the germ theory of hospital sepsis, Lister applied it with a characteristic single-mindedness of purpose to his surgical problem. By 1867 he was able to show that hospital sepsis was preventable using carbolic acid in dressings, on surgical instruments and in a spray. Lister's concept and practice of antisepsis was a fundamental step in the fight against infection and a major contribution to medical microbiology. Recognition, though

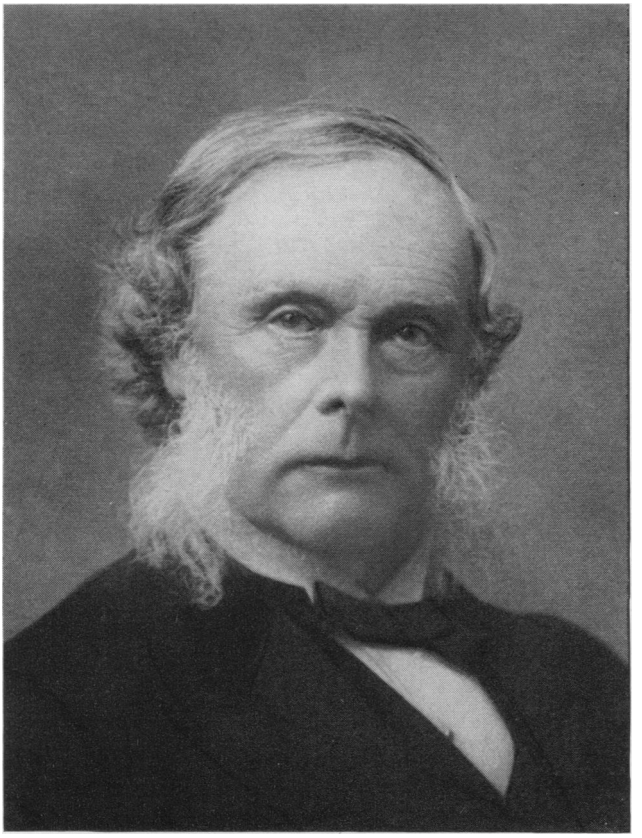


Fig. 2. Lord Lister.

slow, for his achievement, and honours, came to him in his lifetime, a recognition which was glowingly endorsed this very year by this College, 100 years later. Alas, his antiseptic method seemed then too new to be used in the treatment of the battle casualties in the 1870–71 Franco-Prussian War in spite of Lister having written a small pamphlet explaining how his antiseptic method was " applicable to wounded soldiers in the present war!" (Wrench, 1914). The mortality in that war among wounded was appalling. Amputations on both sides were almost 100 per cent

lethal. This tragic experience did much to stimulate certain French and German surgeons' interest in Lister's work and to adopt his method in their civilian hospitals after the war. By 1880 the antiseptic method had become established only to be rivalled by the aseptic or " soap and water " surgery of Spencer Wells and Lawson Tait. By 1900 steam sterilization, and aseptic theatre and ward techniques, were overtaking but not displacing antiseptics in clinical practice. In his unpublished typescript reminiscences entitled " Forty years in surgical harness ", spanning the years 1898 to 1936 (for the perusal of which I am grateful to the Librarian of St. Bartholomew's Hospital), Sir Charles Gordon-Watson records that, " Lister published his first epoch-making paper on antiseptics in 1867 just over thirty years before I qualified. In these thirty years antiseptic surgery grew up and was just emerging into aseptic surgery." Yet he also wrote in the opening chapter that when he qualified in 1898, " Gloves were not worn and a mimicry of asepsis was heavily cloaked with antiseptics."

Wound sepsis in the 1914–18 war

In the medical history of the 1914–18 war it is recorded that in its first months the incidence of wound sepsis among casualties at the base was appalling in its magnitude for, with hardly any exception, every wound was very heavily infected, and in practically every instance the infection had extended beyond its focus of origin. The most serious infections leading to death were streptococcal infections and septicaemia, tetanus and gas gangrene. The disaster had so taken everyone by surprise and caused such despair that it led to the idea that some sinister unknown agency was operating. Small wonder the Director General of Army Medical Services, Sir Alfred Keogh, summed up the situation in October 1914 by saying, " We have in this war gone back to all the septic infections of the Middle Ages ". Progress in antiseptics and asepsis along with surgical experience in the South African War, where the warm dry climate had been favourable, had to some extent induced a complacent outlook towards infection. Sir Almroth Wright, reviewing the situation, was prompted to observe that, " What was intellectually distressing in connexion with all this septic disaster was that the edifice built up by Lister and his successors and by the confident dogmata of surgeons seemed here to lie in ruins ".

Gradually it became obvious that what was wrong was that because of the military situation only the most urgent operative procedures, such as amputation of shattered limbs, could be undertaken at the front, and that practically all other wounds had to be sent down unoperated to the base. As soon as casualty clearing stations, the function of which had been primarily that of evacuation, were equipped with full surgical facilities so that *all* wounds were operated on as soon as the patient was brought in from the battlefield, putrid wound infections became relatively rare.

The nature of wound contamination

It is interesting to note that among the many well known surgeons, pathologists and bacteriologists who devoted their energies in the 1914–18 war to the investigation of wound infection was Alexander Fleming (Fig. 3), whose subsequent discovery was going to revolutionize the treatment of missile wounds in the Second World War.

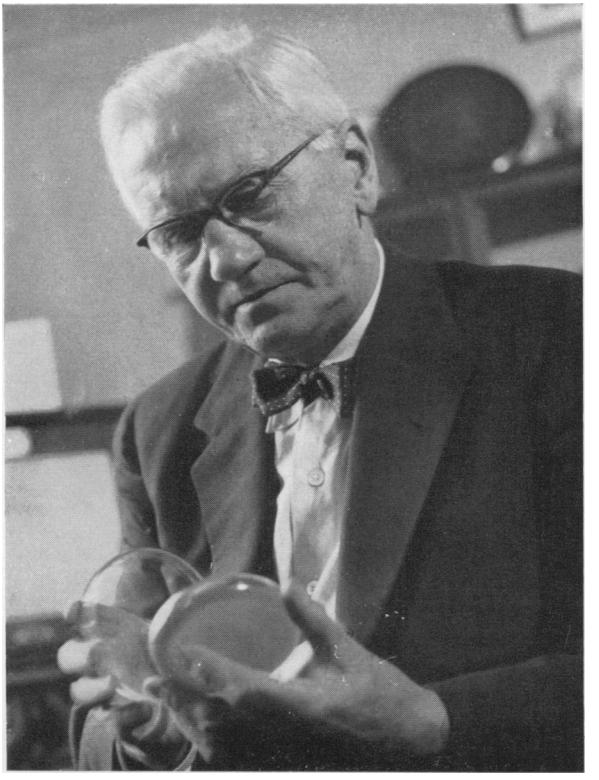


Fig. 3. Sir Alexander Fleming.

Investigation into the part played by the *Streptococcus pyogenes* as a cause of death or delayed healing of wounds was hindered by the more urgent problem of anaerobic infection with tetanus and gas gangrene. From his pre-war observations Lagarde (1914) maintained that human gunshots wounds were never bacteriologically clean.

In 1915 Fleming pointed out that most of the dominant pathogenic aerobes in wounds were streptococci, staphylococci and coliform bacilli and that all were types that could be found on the soldiers' skin and in manured soil. Wound contamination by pathogenic organisms and foreign matter was assumed to be the result of both direct soiling from

skin, clothing and soil and of being carried in by the missile. That another method of contamination obtained was not fully appreciated until after the Second World War.

It was unusual to find bacteria in wounds in the first eight hours after wounding. Up to the twelfth hour aerobes, chiefly cocci, grew more rapidly than anaerobes whose delayed development was due to their arrival in the wound in the spore state. It was also considered that aerobic bacteria had a powerful effect in making conditions favourable for the pullulation of obligate anaerobes. The non-sporing anaerobic bacteria such as the anaerobic streptococci described by Fleming in 1915 received but casual attention. Staphylococci, *B. coli*, *B. proteus* and *B. pyocyaneus* seemed to feature more in the later stages of wounds and were attributed to auto and hospital cross-infection. The high incidence of tetanus complicating missile wounds in the 1914–18 War and the successful measures taken to reduce it have made a well-known story: suffice it to say that the part played by the introduction of antitoxic serum was one of the outstanding achievements of that war.

Gas gangrene

The incidence of gas gangrene in the early part of the 1914–18 war was probably the highest in history. It was between 10 and 12 per cent of all wounded with a mortality of 22 per cent. The disease had been known as far back as the Middle Ages and by the 19th century was called acute spreading traumatic emphysematous gangrene, a name which was shortened to gas gangrene in the 1914–18 war when it assumed tragic proportions.

The condition was ushered in by a striking increase in pain in the wounded part, malaise, restlessness, and vomiting which could become distressing. The symptoms were accompanied by a rise in temperature and pulse rate and by the acute onset of a severe toxaemia leading to a rapidly fatal issue. A patient last seen in good condition could be moribund within a few hours.

The most vulnerable wounds were those of the buttock, thigh and lumbar region where a large mass of muscle was to be found. The wound showed bruised and torn, discoloured and oedematous muscle which neither contracted when pinched nor bled. It gradually became moist with a thin foul-smelling discharge mixed with bubbles of gas and droplets of fat. The odour varied greatly and at times was repulsively foul.

Four organisms, all Clostridia, were identified with the disease: *Cl. welchii*, *Cl. septicum*, *Cl. oedematiens* and *Cl. sporogenes*, the appearance of the local lesion varying with each but all possessed a powerful exotoxin.

Cl. welchii produced a yellowish oedema and much gas in pulpy salmon-coloured muscle. *Cl. septicum* caused a bloodstained oedema, a deep red

colour of affected muscles and much gas. *Cl. oedematiens* was characterized by less gas but the oedema was gelatinous and the muscle pale pink in colour. The condition produced by *Cl. sporogenes* was slower in onset and progress but the muscles became greenish black in colour and the smell was putrid. Similar features were noted in animals with gas gangrene.

In their classical account of the histological appearances in gas gangrene, McNee and Shaw-Dunn (1917) stressed the absence of any inflammatory reaction in the affected muscle.

Comparatively early in the war, Sacquepée, a French pathologist, and Taylor, an American pathologist, advanced the view that it was mainly an affection of muscles, a myositis, and that, except in fulminant cases, it could be aborted by excision of the affected muscles. Clinical observations revealed that the principal cause was a defective blood supply from damage to a main blood vessel, or from constriction by tourniquets or tight plasters, from direct tissue damage or from plugging of wounds. Additional factors were haemorrhage, shock and exposure.

As these clinical and pathological observations were being made it became clear that gas gangrene could be prevented by two fundamental measures. First, the avoidance of all things that might jeopardize the blood supply whether by tourniquet, tight plasters, inefficient splintage, plugging of wounds or the persistence of shock. Secondly, surgical excision of damaged muscle at the earliest possible moment, if necessary cutting short resuscitative measures. After it was found that primary suture led to wound tension and sepsis, excised wounds were left open for drainage and primary suture was delayed for 3–7 days.

Once gas gangrene was established, surgery was even more urgent. If the patient was in good condition, diseased muscles which neither bled nor contracted and were discoloured had to be excised. If the patient was in poor condition, amputation was indicated, though in fulminant cases treatment was practically hopeless. Amputation was regarded as a provisional measure for later revision, and where possible flaps were made, though guillotine amputations were not unknown. The amputation was carried out well above the diseased area either through fracture site, at the next proximal joint and higher if necessary. In the absence of accurate statistics it seems that the surgical measures adopted succeeded in reducing the incidence of gas gangrene to 1 per cent of all wounded, though the mortality rate remained at 22 per cent.

Serum treatment was undertaken by both the French and Germans early in the war but not until 1918 by the British, who were unable to share the enthusiasm of the French and Germans largely because a balanced judgement was hindered by the almost universal mixed infection of wounds, inadequate knowledge of the causative organisms and their identification in a particular case and lack of standardization of the sera.

Until wound excision became the rule many antiseptic substances were developed and used in the treatment of wound infection. These included

Dakin's hypochlorite solution, used by Carrel for wound irrigation, flavine, eusol and bismuth iodoform paraffin paste (B.I.P.P.), but as early wound toilet became the only reliable method of avoiding severe wound sepsis antiseptics assumed a less important rôle except for their use in chronically infected wounds.

Wound sepsis in the 1939–45 war

In the early phase of the Second World War our casualties were minimal until the German forces gained momentum to smash their way to the English Channel. Military surgical methods were based on a 1914–18 outlook and wounds were usually infected. The mistakes of the early part of the 1914–18 War were repeated by the new generation of surgeons who had no experience of war surgery: primary wound suture and limb encompassing plasters were not uncommon, and unnecessary amputations were performed for what was thought to be gas gangrene myositis when the infection was merely due to less harmful gas-forming organisms. Trueta in the Spanish Civil War had revived for his wounds the old-fashioned closed-plaster treatment of compound fractures and osteomyelitis, and this method was adopted in 1939 with some success.

The high degree of mechanization of the enemy and the experience of long distances to be covered in the hot dry Libyan desert did much to stimulate the development of mobility in our Forces. In the desert campaign sulphonamides were used more widely and, along with the hot environment, emphasized the fluid needs of patients. Wound infection and gas gangrene, though still a bogey, were much less common than in the 1914–18 war, yet MacLennan (1943) in the Middle East was able to add significantly to our knowledge of anaerobic infection. He found that up to 30 per cent of all wounds (sustained in the Middle East 1939–42) contained sporing anaerobes which disappeared rapidly, only 5 per cent of wounds showing a cellulitis. Gas gangrene (clostridial myositis) complicated only 0.32 per cent of all wounds; this was in spite of prophylactic sulphonamides and antitoxin which led him to question the adequacy of wound debridement being carried out. He emphasized the importance of recognizing anaerobic cellulitis, a non-fatal condition, and streptococcal gangrene, due to the anaerobic streptococcus, neither of which conditions invited the ruthless surgery meted out to clostridial myositis. He was also able to show that the untouched desert sand was practically free of pathogenic anaerobes and that the main source of infection was the clothing of the fighting man.

The sulphonamides overcame systemic infections, though locally in wounds it was disappointing. The highlight of the war was the introduction of penicillin, which revolutionized the treatment of war wounds by defeating local sepsis and increasing the scope of surgery without displacing it. Along with penicillin, wound surgery was given a tremendous impetus with more efficient resuscitation as a blood transfusion service

gained momentum, surgeons became more experienced, mobile surgical units became more plentiful and more aircraft speeded casualty evacuation. When the end of the 1939–45 war came, the incidence of wound infection and disability was the lowest ever recorded. Yet the overall incidence of gas gangrene was only just under 5 per cent and the mortality rate significantly higher than in the First World War: it was over 30 per cent.

The contribution of ballistics to wound infection

In spite of the strenuous measures taken to conquer missile wound infection in both the First and Second World Wars the particular liability of these wounds to infection was never satisfactorily explained until during and after the latter war, when progress had also been made in the medical aspects of ballistic science.

The passage of a missile through any medium causes laceration and crushing in its path. With missiles of low velocity, i.e. less than 1,000 ft./sec., such as revolver bullets, spent rifle bullets and metal fragments, the damage caused is usually confined to the missile track.

During the 19th century missile velocities increased as the result of several improvements in firearms. A gas seal had been introduced between ball and powder, then both were enclosed in a cartridge case. Gun barrel rifling was introduced and a breech-loading mechanism was invented. Then came the development of the smokeless powders, nitroglycerine and nitrocellulose and the pointed bullet. The resultant increased missile velocities caused greater destructive effects and wounds began to display explosive features. This led to international concern as it was thought that bullets themselves exploded in the tissues, a concept we now know to be false.

Although the strike energy of a projectile could be calculated from the equation: Strike energy $= \frac{1}{2}$ mass $(\text{velocity})^2$, both Woodruff (1898), and later Stevenson (1910), showed that wounding was dependent, *not* on strike energy, but on the amount of energy absorbed by the target tissue from that released by the missile as it was retarded in the tissue. This absorbed energy has also been shown to be directly proportional to the cube of the missile's velocity (Callender and French, 1935), to its presenting cross-sectional area, to its instability (such as a bullet's yawing motion), and to the density of the target medium. All these factors increased the missile's rate of retardation. Hopkinson and Marshall (1967) considered that, " yaw is the next most important factor after velocity in determining the extent of damage caused by a bullet ". Any deviation from the axis of flight increases the presenting area of the missile, thus increasing its retardation and loss of energy. The degree of tissue damage can be extensive if most of the missile's strike energy is released by rapid retardation if it is yawing or when it strikes a dense medium such as bone: indeed such a rapid retardation may cause fragmentation of the missile (Herget, 1953).

Another feature of the effect of the passage of a missile when it strikes and compresses the surface of a medium is the creation of a shock wave which moves ahead and radially at a velocity greater than sound in the medium and though this shock wave may be resisted by muscle and bone it may produce hydraulic effects on gas-containing viscera. In addition to the track carved by a missile and the shock wave it creates there remains to be explained the cause of the " explosive " effect.

The accelerated particle theory of " explosive " wounds

Several theories were offered to explain the explosive features of 19th century firearm wounds. Sir Victor Horsley (1894) considered that the cause of disruption of tissue was the high velocity and spin of the bullet. None of the theories, however, was universally accepted. The most likely was that of Woodruff (1898), since referred to as the accelerated particle theory (Harvey *et al.*, 1945). It was based on experiments in which bullets and steel balls had been fired through tomatoes and tins of sand. Woodruff postulated that during the passage of a missile a cavity was created in the target medium due to the accelerated centrifugal displacement of particles in the medium, and he suggested that air was sucked into this wound cavity. He called the effect cavitation, borrowing a marine engineering term introduced in the previous year to describe a cavity of partial vacuum formed in front of a ship's propeller revolving at a critical speed (Thoresby, 1966). Understandably the theory had a sceptical reception as the wound cavity could neither be seen nor demonstrated. Indeed, as late as the 1914–18 war doubt still remained, and in the opening chapter of Volume 1 of the Medical History of that war the term " cavitation " was referred to only speculatively. Confirmation had to wait until the Second World War, when in 1941 Black *et al.*, employing the Boys (1893) modification of the spark shadowgraph system of Mach and Salcher (1890), were able to demonstrate photographically this transient instantaneous cavitation phenomenon by firing spheres and bullets at varying speeds through both gelatine blocks and rabbits' legs. It has since been demonstrated (Harvey *et al.*, 1945) with modern high-speed cinematography combined with microsecond surge radiography with which it has also been possible to show that the cavitation phenomenon could be produced in a vacuum (Harvey *et al.*, 1962).

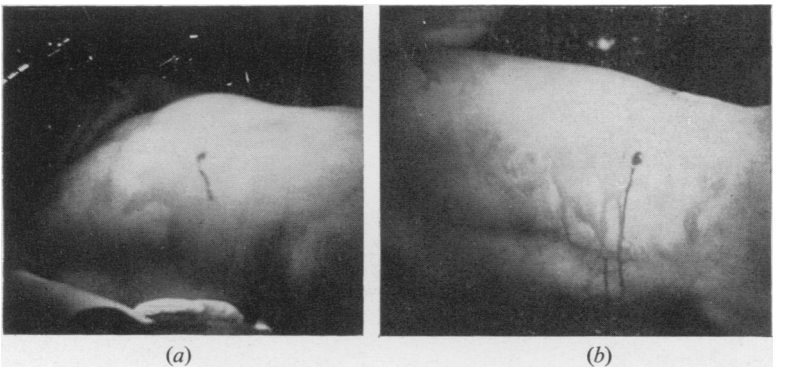
Temporary cavitation

Temporary cavitation is now regarded as the important feature of all high velocity missile wounds in addition to the damage in the track of the missile and its shock-wave effect. The momentary centrifugal displacement of tissue particles caused by the absorption of released energy creates a temporary pulsating cavity in which pressure is sub-atmospheric. Air is successively sucked in and blown out of the cavity through both entrance and exit wounds until the cavity finally collapses. Experimentally in both the intact animal (Ainsworth, 1961) and isolated organs

(Krauss, 1957) a direct relationship has been shown to exist between the absorbed energy from a projectile, the peak cavity volume and the irreversible tissue damage produced.

The shape of the temporary cavity depends on the shape and presentation of the missile. With a sphere it is fusiform in longitudinal section, with a yawing bullet there may be several large temporary fusiform cavities connected by smaller ones.

The area of tissue damage caused by the temporary cavity can be quite extensive. There can be tissue pulping, blowing asunder of fluid-filled viscera, remote damage to blood vessels, fracture of bones untouched by the missile, and shattering of bone when it is struck with scattering of bone splinters. High velocity missiles may have singularly small entrance and



(*a*) (*b*)

Fig. 4. (*a*) 7.62 mm. bullet entrance wound in right hypochondrium of a soldier. (*b*) 7.62 mm. bullet exit wound in right loin in the same soldier. In spite of the small wounds the underlying intra-abdominal damage was extensive.

exit wounds (Fig. 4*a* and *b*). Unstable irregularly shaped metal fragments from exploding devices will cause ragged wounds of varying size and will tend to lodge in the body carrying in with them bits of clothing, dirt and foreign matter, not to mention the secondary effects from the scattering of bone splinters.

By 1912 bullet muzzle velocities were approaching 2,800 ft./sec., doubling their strike energy and extending the range in which yaw occurred, thus increasing retardation and release of energy in target tissue to cause significant wound cavitation explosion effects. The deadly results were observed in the 1912–13 Turko-Balkan War by Lagarde (1914) and have continued to be observed since. The modern 7.62 mm. NATO self-loading rifle and automatic weapons, and the recently introduced light American Colt Armalite rifle with a 0.223-inch bullet (muzzle velocity 3,250 ft./sec.) have an even more devastating wounding potential.

The mechanism of wound contamination

It having been demonstrated that cavitation was the main damaging

effect of high velocity missile wounds the part it played in the contamination of a wound had to be ascertained. Lagarde (1903) had already shown that bullets contaminated with organisms were not sterilized when fired from a rifle and that they carried the organisms into the resulting wound. He demonstrated this by causing gas gangrene in guinea pigs by firing into them bullets contaminated with "bacillus aerogenes capsulatus of Welch", and it was probably the first time that deliberate wound contamination had been induced in an experimental animal with histotoxic clostridium.

That the cavitation effect accompanying the passage of a high velocity missile could be responsible for drawing in contaminating matter from the target surface through entry and exit wounds was shown by Dziemian and Herget (1950) using barium sulphate powder and dyestuffs, by Ziperman

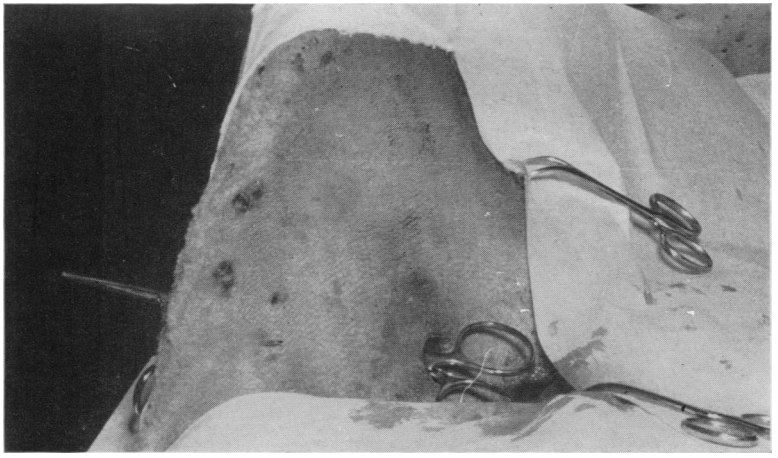


Fig. 5. The standard experimental bullet wound through the quadriceps femoris muscle of a sheep.

(1961) using coloured powders and by Thoresby and Darlow (1967), who fired a sterile bullet through a cloud of thermolabile organisms as well as through a piece of contaminated cloth impregnated with them. Whether the cloud or piece of cloth were on the entrance wound face of the target gelatine block, or on the exit wound side, the organisms could be grown in the missile track and in the crevices left by the collapsed temporary cavity. The same effect was produced with resulting fatal gas gangrene when a bullet was fired into a sheep's thigh through a piece of cloth (simulating clothing) which was impregnated in turn with measured spore suspensions of *Cl. welchii*, *Cl. oedematiens* and *Cl. septicum* (Thoresby and Watts, 1967). Death took place within 60 hours at the most, whether the impregnated cloth was on the exit or the entrance side of the sheep's thigh. When the bullet had pierced the cloth, having made a superficial wound and missed muscle, a non-fatal anaerobic cellulitis occurred. When the bullet made a muscle wound but missed the cloth an uninfected wound

resulted. When the cloth had been pierced on the exit face of the thigh, fibres were also found in the wound which led Thoresby and Watts to suggest that cavitational suction was more important than implantation of contamination in high velocity missile wounds.

Histological features of the uncontaminated missile wound

Le Gros Clark and Blomfield (1945), Krauss (1957) and Harvey *et al.* (1962) have studied the histological features of bullet muscle wounds in various animals, and Dziemian *et al.* (1961) found that, in goats, bullet wounds of the thigh had healed uneventfully providing major bone and blood vessel damage had been avoided. The histological features of a bullet muscle wound from injury to healing were studied in detail in sheep by Hopkinson and Watts (1963). Their method became a standard one for our subsequent studies (Fig. 5). They fired a 0.22-inch bullet at 1,600 ft./sec. into the quadriceps femoris muscle of an anaesthetized sheep and produced a non-fatal wound. Using intravenous Indian ink perfusion a zone of muscle corresponding roughly to the area of temporary cavitation was shown to be ischaemic and it increased in size up to 12 hours. With Geimsa stain, which stains normal muscle pink, they showed that damaged muscle was coloured blue in varying shades. Hopkinson (1964) postulated that this colour change was due to an alteration in the physical structure of the damaged sarcoplasm. In the absence of major blood vessel damage and infection phagocytosis of dead muscle took place, and some muscle regeneration, over the next three months when the wounds healed leaving a thin fibrous scar.

The source and development of wound infection

Many observers (Fleming, 1915; MacLennan, 1943; Altemeier and Gibbs, 1944) have emphasized that all battle wounds are contaminated with a variety of flora including pyogenic cocci and pathogenic clostridia, but that their presence was no indication that infection would develop for they tended to disappear on subsequent days. These organisms have been found on the skin and clothing of wounded men and in the soil. The ultimate origin of the clostridia is in the large intestine of animals and especially in man himself. Price and Shooter (1964) have shown that commensal strains of *Cl. welchii* excreted from the human bowel were capable of forming appreciable amounts of a-toxin.

The presence of a blood clot in a wound encourages the growth of organisms. For the germination of clostridial spores and formation of their powerful toxin a greatly reduced oxygen tension is necessary: this is found in ischaemic and necrotic tissue, especially muscle.

No practical method has yet been devised, short of the appearance of clinical signs, to determine in which missile wounds gas gangrene will develop. With large open wounds muscle damage will be obvious, but with wounds caused by high velocity bullets showing only small entrance

and exit wounds the extent of damage can only be revealed by surgical exploration.

Experimental investigation into treatment methods

Sulphonamides were a great boon in the treatment of missile wounds among the British, Americans and the Germans in the Second World War, and their main value lay in their control of the systemic effects of wound infection. They seemed to have little effect when applied topically especially in deep wounds, though Domagk (1942) had maintained that a sulphonamide powder called Marfanil, also known as sulfamylon or mafenide (4 (aminomethyl) benzene sulphonamide hydrochloride), given orally, would protect rats against gas bacillus infections. This was disputed by Schreuss (1942), who had, however, been able to prevent lethal gas gangrene in guinea-pigs when he had applied sulfamylon topically to incised muscle wounds contaminated with manured earth.

Jelenko *et al.* (1966) have referred to the ill-designed German war-time experiments carried out on concentration camp prisoners, on whom incised muscle wounds were inflicted under anaesthesia and contaminated with streptococci and gas gangrene organisms in order to test the effectiveness of local and systemic sulphonamides. The results seem to have been inconclusive except to emphasize the value of surgical measures alone.

Jelenko *et al.* went on to suggest, however, that the effectiveness of topical sulphonamides in severely contaminated wounds, and those in which the blood supply had been significantly impaired, had been obscured in German and American war-time reports by the larger number of wounds which may not have required topical therapy. This has since been studied experimentally.

Massive open wounds have been inflicted on the thighs of anaesthetized goats using a high explosive charge of tetryl (Oschner *et al.*, 1958; Lindsey *et al.*, 1959). The severe soft tissue and vascular damage inflicted invariably resulted in death. Mixed flora were found in the wounds and *Cl. welchii* were always present. These goats were susceptible to anaerobic infection and could develop it spontaneously. There was also a relationship between the number of *Cl. welchii* in the wound and survival. Topical therapy alone, especially with a spray of sulfamylon, was exceedingly effective in controlling the growth of organisms and contributed significantly to the survival of the animals with these massive, undebrided, *Cl. welchii* infected high explosive wounds (Mendelson and Lindsey, 1962).

Surgical measures

In contrast with these massive high explosive wounds, the treatment of experimental high velocity *bullet* wounds has also been studied using the sheep bullet wound preparation of Hopkinson and Watts (1963) and the deliberate clostridial contamination method of Thoresby and Watts (1967).

The untreated sheep was used as a control as it usually developed fatal gas gangrene within 60 hours of wounding. The appearances of the local lesion had to meet the histological criteria laid down by McNee and Shaw-Dunn (1917) as amplified by Robb-Smith (1945), who, incidentally, considered the term " myositis " to be inappropriate because of the striking absence of a local inflammatory reaction. He preferred the term " myonecrosis," which we have now adopted. The contaminating organism used was *Cl. oedematiens* spores, because the sheep used were already actively immunized with *Cl. welchii* toxoid. Operation was carried out in each case six hours after wounding, when wound infection should be developing. Simple incision joining entrance and exit wounds across the

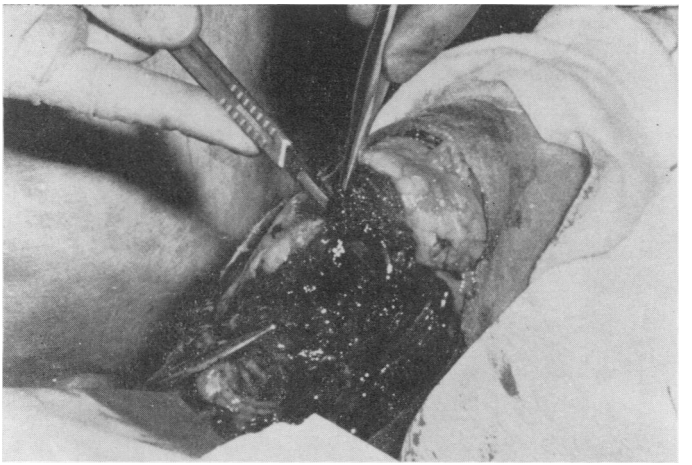


Fig. 6. Excision of damaged muscle in the standard sheep bullet wound.

sheep's thigh, laying the wound open down to the missile track, was compared with excision of all discoloured, non-bleeding and non-contractile muscle (Fig. 6). The results are shown in Table I, in which it will be seen that incision alone failed to prevent fatal gas gangrene. A significant prolongation of survival time was obtained with wound excision (Thoresby and Matheson, 1967). In these thigh wounds longitudinal incision and liberal incision of fascia to release tension was no more successful than simple transverse incision.

Antibiotics

Soon after its introduction in the Second World War penicillin quickly displaced the sulphonamides in the effective control of wound infection. Penicillin was bactericidal, it lacked the harmful effects of sulphonamide overdosage and sensitivity, it could be introduced into infected cavities with safety and it was effective against a wider range of organisms.

The effect of penicillin has been studied (Thoresby and Matheson, 1967) in the contaminated sheep bullet wound preparation: penicillin alone, given

intra-muscularly three-quarters of an hour and six hours after wounding, prevented fatal gas gangrene and was more effective than either wound incision or wound excision.

Further studies revealed the remarkable effectiveness of penicillin alone in preventing pyogenic and gas gangrene infection in these sheep bullet wounds. It was found that the commencement of a course of penicillin could be delayed up to nine hours after wounding with survival of the animal and without surgical measures being undertaken. Delay beyond nine hours led to an increasing mortality rate from gas gangrene (Owen-Smith and Matheson, 1968). Similar results were obtained with intramuscular injections of tetracycline (Owen-Smith, 1967).

TABLE I

COMPARISON OF INCISION WITH EXCISION OF CONTAMINATED BULLET WOUND OF SHEEP'S THIGH

	Survival Time (in Hours) after Wounding		
	A	*B*	*C*
Group	*Control*	*Incised*	*Excised*
1	200 (a)	40	200
2	40	60	12 (c)
3	30	30	200
4	30	30	40 (b)
5	200 (a)	20	200
6	200 (a)	40	200
7	60	30	100
8	50	60	140
9	50	20	30 (c)
10	40	200 (a)	200

The excess of " Excision " over both " Incision " and " Control " is significant.

Notes: (*a*) Superficial wound only.
(*b*) Amputation indicated.
(*c*) Post-anaesthetic pulmonary deaths.

Polyvalent gas gangrene antitoxin

The prophylactic value of gas gangrene antitoxin has clinically been somewhat overshadowed, like the sulphonamides, by antibiotics, but it is interesting to note that in the contaminated sheep bullet wound preparation (Owen-Smith, 1968), using intramuscular polyvalent gas gangrene antitoxin alone in the unwounded limb, prevented gas gangrene in 10 out of 11 sheep. The wound track in the survivors usually showed an abscess in the pus of which *Cl. oedematiens* spores were found and cultured. Injection of the local lesion with gas gangrene antitoxin has not yet been tried in these animals. The M.R.C. memorandum on gas gangrene (1943) had suggested that there was little advantage in this method although later Robb-Smith (1945) advocated it where adequate surgery could not be performed. He contended that the local injection of antitoxin could inhibit the cytolytic action of *Cl. welchii* filtrate which caused the lack of cellular reaction which is characteristic of gas gangrene of muscle.

Interpretation of experimental results

The extent to which the results of these animal experiments can be applied to human missile wounds requires caution.

The experiments have shown that antibiotics in adequate doses given early will prevent serious wound infection from both pyogenic and anaerobic organisms. The sheep wound, however, was produced by a bullet of a known and only moderate high velocity of 1,600 ft./sec. in muscle which was comparatively less bulky than that of man. Modern bullets have a velocity of over 2,500 ft./sec. and are more destructive despite small exit and entrance wounds. Unless the speed of the bullet causing a man's wound is known, the amount of tissue damage will remain in doubt and an early attempt should always be made to explore the wound to remove dead tissue and blood clot. Antibiotics are an essential safeguard against delay in surgery.

From the prophylactic aspect sulphonamides in human experience have not been as effective, systemically and locally, as antibiotics, but the success of topical sulfamylon in massive high explosive muscle wounds in goats has an application to human wounds when surgery is likely to be delayed, providing toxic absorption effects are anticipated.

Prophylactic polyvalent gas gangrene antitoxin carries the hazard of anaphylaxis in human beings. Any occasion, especially in war, when mass casualties might overwhelm surgical resources, surgery for the severely wounded may have to be delayed indefinitely. This would create an ideal situation for the development of gas gangrene. Whatever the remoteness of such a possibility there is a case for the development of a gas gangrene toxoid to induce active immunity.

Missile wound infection since 1945

Although missile wound infection has been significantly reduced in all campaigns since the Second World War by the use of antibiotics, especially penicillin prophylactically, it has by no means been abolished. Wright (1956) observed that in the Korean War 9 per cent of the wounds in patients arriving in Japan were infected, mostly superficially, and that 2 per cent were massive stinking wounds attributable to inadequate primary surgery. The same reason was given by Latta (1951) for the three cases of gas gangrene occurring among 1,850 wounded patients.

In the Borneo Confrontation of 1963–65, when bullet wounds predominated, Wheatley (1967) reported that the incidence of sepsis was very low and mostly superficial causing mainly a delay in wound healing. He related wound sepsis to the severity of tissue damage and to pre-operative delay. No instances of gas gangrene occurred. All the wounded men were given either penicillin injections or oxytetracycline tablets orally as soon as possible after wounding.

The Vietnam War started in 1963 and still continues. Wound sepsis has been low in spite of an initial spate related to surgical inexperience mani-

fested by inadequate surgery and primary wound suture. In a series of 60 wounded Australian servicemen, Moffat (1967) has reported an incidence of nearly 3 per cent wound sepsis. He considered that hospital cross-infection may have been responsible for half of the serious sepsis which occurred in 11 severe wounds. Gas gangrene still occurs in spite of antibiotics, for he had two cases in patients with multiple mine wounds of the lower limbs and both required amputation. Multiple mine and bullet wounds pose a serious challenge to the forward surgeon, for surgical attention to them is time consuming and likely to be subordinated to more severe wounds.

Tetanus

Tetanus has been absent as a complication of missile wounds in British servicemen for many years since active immunization with tetanus toxoid has superseded prophylactic passive antitoxin. When an actively immunized man sustains a missile wound he is given a single re-inforcing dose of tetanus toxoid. When active immunity is in doubt, not known, or absent, and especially if wound toilet is delayed more than six hours, or is inadequate, there is the choice of three prophylactic measures. First, the injection of tetanus antitoxin of equine origin, keeping in mind sensitivity reactions which are relatively common and sometimes dangerous. Secondly, an injection of human antitetanus gamma globulin which has so far been scarce and, thirdly, the prompt commencement of a prophylactic course of intramuscular penicillin injections or oral tetracycline, the dosage being proportional to the severity of the wound. Since antibiotics may fail to eliminate *Cl. tetani* from the wound (Smith, 1964) they should be continued until the wound is bacteriologically clear of the organisms or until active immunity has been adequately established by toxoid.

Established gas gangrene

In this address I have confined myself mainly to the prevention of wound infection, but as gas gangrene remains the most dreaded complication of missile wounds, a brief reference to the treatment of the established case is pertinent. Hyperbaric oxygen at three atmospheres combined with antibiotics has become the most successful method in the treatment of the infection for it seems that surgery thereby can be deferred until hyperbaric oxygen has controlled the disease. Surgery then can be confined to the excision of sloughs and skin grafting (Van Zijl *et al.*, 1964).

CONCLUSION

While the campaigns that have followed the two World Wars could compare with them neither in numbers engaged nor casualties, weapons have become more complex and their missiles more destructive. Nevertheless more lives have been saved by improvements in medical organization in the fighting zone, by better first-aid training, by speedier casualty evacuation, especially by air, and by improved resuscitative measures for shock.

The contribution of antibiotics to the reduction of wound sepsis and its complications is beyond praise for they have facilitated earlier wound healing and skin cover as well as surgical procedures such as blood vessel repair previously hazardous. No less important is the blessing of tetanus toxoid immunization. While antibiotics can permit delay in primary surgery the importance of early wound toilet should never be overlooked, especially in severe wounds and multiple small wounds, for gas gangrene still occurs.

Early wound surgery comprises wound exploration within six hours, the removal of foreign material and blood also assisted by gentle irrigation and the excision of all damaged tissue especially discoloured, non-bleeding and non-contractile muscle. Where the wounded man has to be evacuated to another medical unit, wounds, including amputation stumps, should not be sutured but left open, and covered, but not plugged, with a dressing. Wounded limbs should be immobilized in well padded but split plasters. Serous cavities should be closed with drainage leaving the skin and muscle layers open. Wound closure can be delayed until the wound shows signs of clean granulations usually within seven days. Primary suture is permissible for hands and fingers to cover exposed tendons and on the face. Internal fixation of compound fractures in battle surgery will court disaster. These surgical principles were developed by bitter experience in the First World War and hold good to-day especially when adverse circumstances prevail. The surgeon who ignores them does so at his peril. In spite of antibiotics, missile wound sepsis to-day is still related to the severity of the tissue damage, to pre-operative delay and to faults in surgical technique.

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PROCEEDINGS OF COUNCIL IN MAY

AT A MEETING of the Council on 9th May 1968, with Professor Sir Hedley Atkins, President, in the Chair, Begley Prizes were awarded to R. W. Hoile, of Charing Cross Hospital Medical School, and to M. C. E. Hutchinson, of Guy's Hospital Medical School.

Mr. E. H. Cornelius, M.A., was appointed Librarian of the College from 25th September 1968, in succession to Mr. W. R. LeFanu, who is retiring from office on that date. Mr. Cornelius has served in the Library since 1948 and has been Assistant, later sub-Librarian, since 1951.

Mr. R. M. Gibson, F.R.C.S.Ed., Consultant Neurosurgeon, Leeds General Infirmary, was admitted to the Fellowship *ad eundem.*

Mr. J. H. Peacock, F.R.C.S., attended to receive the Jacksonian Prize for his dissertation on " Experimental liver transplantation ". Mr. Peacock previously won the Jacksonian Prize in 1953 for an essay on " Diaphragmatic hernia ".

A presentation was made by Council to Mr. J. C. Higgins on his retirement from the staff.

Diplomas of Membership were granted to 251 candidates. The following diplomas were granted, jointly with the Royal College of Physicians: *Anaesthetics* (1), *Child Health* (1).