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COMBAT CASUALTY CARE: CAN TECHNOLOGY HELP?*

Remarkable success has been achieved in the management of combat trauma even as developing military technology has increased the severity of injuries. The environment of future conflicts could negate some of these gains. New technologies with potential for application in the field to reduce mortality and incapacitation are discussed.

> The Wound . . . doth require to be made one again. . . . To effect this is the work of Nature and Art . . . and unless both the vital Faculties and the nourishment of the Part do assist the Art of the Chirurgeon, it will be a lost labour. . . .
>
> Richard Wiseman[13]

INTRODUCTION

Pare [7] and Wiseman[13] in the 16th and 17th centuries, respectively, delineated the impact of weapons technology on military trauma and the role of the surgeon in trauma care. Even earlier, several texts were directed primarily to combat casualty care.[3] The innovation in technology and treatment marking the beginning of the modern period starts with Pare's insistence upon sanitation and the natural healing of wounds:

> Thus I have thought good to recite and set downe. That the Readers may understand that I for 30 years agoe had found the way to cure wounds by Gunshot without scalding oyle or any other more acrid medicine. . . .

By the late 16th and early 17th centuries, varied instrumentation was available, designed for trauma surgery. Richard Wiseman's emphasis on adaptation of trauma technique to the individual case, consultation with experienced colleagues, and the use of sophisticated instruments[6] carried on the tradition of Pare and marked a major milestone in the advance of military surgery. Wiseman's description of (relatively) high-velocity wounds is classic:

> Wounds made by Gun-shot are the most complicated sort of Wounds that can be inflicted: For they are not only Solution of continuity, but leave joined with them Contusion, Attrition, and Delaceration in a high and vehement kind. To this we may add all sort of Fractures and Accidents as Haemorrhagia, Inflammation, Erysipelas [skin infection], Gangrene and Sphacelus [necrotic tissue]; besides the extraneous bodies which are violently carried in the wound, and multiply Indications.

The primary asset of modern combat surgery is not technological, but rather, human. It is the well-trained and experienced surgeon applying the concepts that have developed within the last four centuries, most particularly concepts that have developed within the last century: asepsis, debridement (removal of dead tissue), and delayed primary closure, together with prevention and treatment of hemorrhagic shock and use of topical and systematic antibiotics.[9,11,12] Additionally, from at least the Korean War on, techniques of maxillofacial, ocular, and vascular surgery have materially reduced the scale and number of permanent impairments.

A number of technically interesting, potential additions to the surgical armamentarium constitute the basis of this discussion. However, whenever we try to improve a system by introducing new technology or new procedures, the bottom line is always, will the new application help or, in fact, hinder?

I will discuss:

1. How new technology may assist basic needs such as sterile water and sterilization,
2. Improvements in radiologic imaging and the application of ultrasonics,
3. Recent results in electronarcosis,
4. Patient-monitoring methods,
5. Miniaturization of devices for patient support,
6. Computer-aided data systems,
7. Automated triage.

Today the technologist knows that he must analyze not only the available technology but also the system to which it will be applied. Medicine first recognized the systems concept, dividing the body system into various subsystems — genitourinary, digestive, circulatory, respiratory, and so on,[10] with Harvey's description of the circulatory system[4] marking the beginning of the modern era.

The essence of systems analysis is to reduce iteratively a complex system into smaller units. These units, the subsystems, must be chosen so that either there is a weak coupling between them or, which occurs less frequently in practice, there is a well-defined transfer function of effect between them. The obser-

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vation of, or modification of, a subsystem, however, must always be viewed in terms of what that observation or change implies for the entire system. Claude Bernard,[1] in discussing physiological experimentation, states this succinctly:

> . . . if we break up a living organism by isolating its different parts, it is only for the sake of ease in experimental analysis and by no means in order to conceive them separately . . . to ascribe to a physiological quality its value and true significance, we must refer it to this whole; and draw our final conclusion only in relation to its effects on the whole. . . . Physiologists and physicians must therefore always consider organisms as a whole and in detail at one and the same time. . . .

The combat casualty care system consists of both people and equipment. The introduction of new technology should maintain or create a balanced system, with appropriate trade-offs for cost, logistics, and personnel and with reasonable certainty of improvement of the overall capability.

The Model

In order to see what technology exists that can be applied or adapted to the combat casualty problem, a model system has to be developed that is simpler than the real world. The trauma victim is assumed to be initially healthy, within a prime age bracket, and in good physical condition. The classic *bêtes noires* of military medicine — the ever-present upper respiratory infections, gastrointestinal disturbances, and venereal disease complications — are ignored, as are the added burdens undertaken by the military to assist local populations and indigenous troops, who are generally in a much poorer state of health than the military.[43,53,62,72] Bacteriological, chemical, and radiological weapons are assumed to be not present. These would introduce major complications in handling trauma under decontamination procedures.

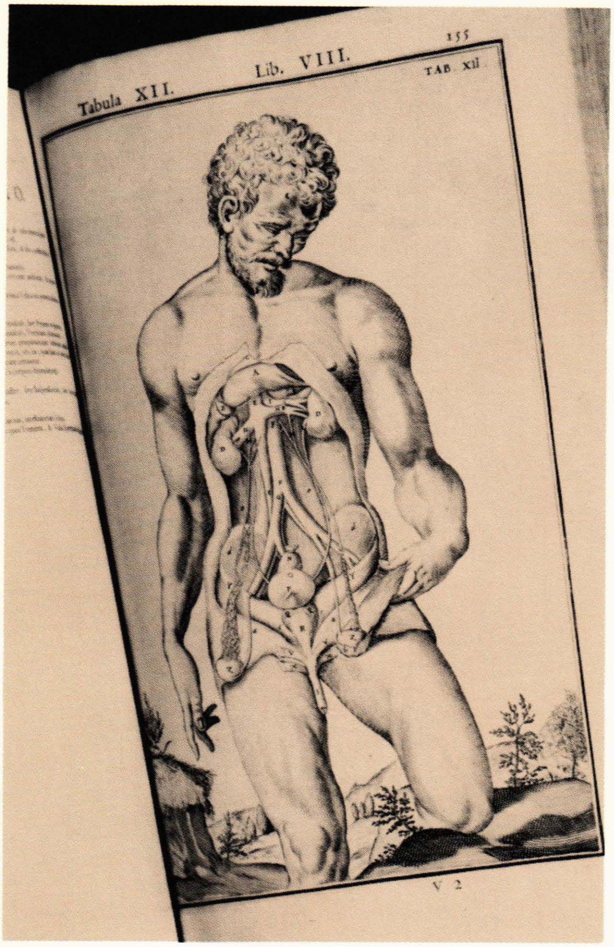
The trauma considered is manifested as penetrating wounds (and fractures), other blast injuries, and burns. Several characteristics of modern warfare must be kept in mind, most particularly the wound ballistic phenomena produced by high-velocity missiles. Modern rifles, such as the M-16 and AK-47, and fragmentation devices (at least at close range), such as landmines, artillery shells, and aerial bombs, because of the high brisance of modern explosives, produce high-velocity missiles that enter the body,[35,44,55,56] producing cavitation and shock waves.[14] These result in extensive damage reaching well beyond the linear path of the projectile. The increasing use of plastics and nonmagnetic metals can make diagnostic techniques, especially imaging, very difficult indeed. Even without penetration, blast phenomena present special problems in terms of internal lacerations, otic trauma,[95,100] and severe ocular damage of the globe by overpressure and of the cornea and surface in general by impinging particles both from the weapon and the surroundings.[96-99]

Von Gertsdorff, here illustrating the extraction of an arrow, published one of the earliest treatises devoted entirely to combat casualty care in 1517.[3]

Burns may be complicated by chemicals present,[91,92] such as white phosphorus from flares and other pyrotechnic devices.

The model must next look at the distribution of medical resources and the system of bringing them and the patient together.[18] These resources extend from the battlefield to an evacuation center at a comfortable distance from the forward edge of the battle area and consist of increasingly intensive echelons of care: corpsmen, first aid, resuscitative support stations, primary definitive surgical care, and, finally, the evacuation center.[20]

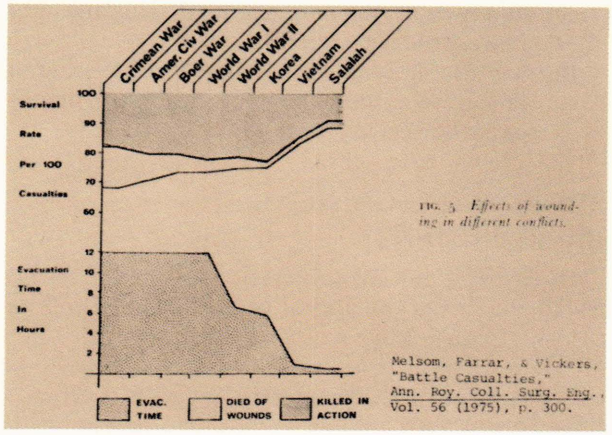
The impressive survival statistics for the wounded who reached surgical care in Vietnam,[33,34,38,40,42,46] mirrored also on the Israeli side of the recent Middle Eastern wars[64,67,99] and in various "local actions" such as Northern Ireland[59,61] and Oman,[65] have been attributed to the prompt treatment of hemorrhagic shock and the short time interval between wounding and arrival at a point of definitive surgical care.[19] In Vietnam, for example, only about 2.5% of the wounded in action who reached the surgical stage did not survive, compared with a similar value in Korea, 4.5% in World War II, and 8.5% in World War I.



The concept of a system, a complex of correlated, interacting, and semi-independent components, first appeared in medicine, as illustrated in this 17th century plate of the genitourinary system.[10]

Prompt initial treatment at the first aid and second echelon levels to minimize hypovolemia (loss of body fluid volume) provided a ratio of wounded in action to killed in action of about 4.5/1 in Vietnam as contrasted with a ratio of 2.8/1 in Korea. The key instrument here, of course, was the helicopter: one-half to two hours to the surgical care unit, a total of perhaps five to six hours until surgery, are typical time intervals.

The above would appear to provide a neat workable model to define entry points for new technology. Unfortunately, it may be wrong in at least one very critical aspect: the critically short time interval between wounding and surgery may no longer be achievable. The ability to use helicopters depends on control of the air space. However, the ever-increasing variety and profusion of hand-held, precision-guided antiair weapons tend to negate the ability to control air space to the point that would permit the use of helicopters.[15] If we have to return to a ground transport system over rough terrain, then the transit delay time may be more typical of World War II, perhaps 10 to 15 hours. Furthermore, new weapons technology, e.g., guided surface-to-surface missiles, may



The significance of shortening the evacuation time (from injury to primary surgical care) is graphically and dramatically portrayed here for a series of conflicts from the Crimean War to Vietnam (from Ref. 64). (Salalah, Oman, refers to casualties during a 1972-1973 uprising.)

make close-in or permanent surgical installations difficult, if not impossible, to maintain. Thus, greater mobility and smaller unit size would be required, with wider distribution of surgical specialties, generally less consultative capabilities at any one site, and the corresponding need for carefully determined casualty routing.

Technology Assessment

A general assumption in assessing a new addition to the casualty care armamentarium is that it be capable of coexisting with mud, sand, water, heat, and cold. The primary focus of compatibility should be on use in the field. The classic requirement of military gear of withstanding a four-foot fall from the tailgate of a truck at 45 miles per hour can be, in fact, stark reality. In the naval service, shipboard installations are possible, providing substantially more benign environments and tolerance.

In discussing potential technical marvels, let me stipulate a checklist of necessary features:

1. Does it improve an existing function or provide a new and necessary capability?
2. Are the dimensions and weight compatible with field use?
3. Are the basic consumables (electric power, water, special gases, etc.) logistically tolerable?
4. Is it adequately rugged relative both to the natural environment and to the G.I.?
5. Is it maintainable in the field in terms of available technical talent and the logistics chain?
6. Is its operation adequately simple and standardized for all who might have to use it?
7. Is there any new hazard being introduced (nuclear materials, toxic gases, high pressures, etc.)?
8. Is it flexible enough to warrant its introduction in terms of the number of cases to which it can be applied?

9. Can it be available in adequate quantities in a reasonable time frame?
10. Are the acquisition cost and time (including new developments or modification of an existing device) acceptable?

PROPOSED TECHNICAL IMPROVEMENTS

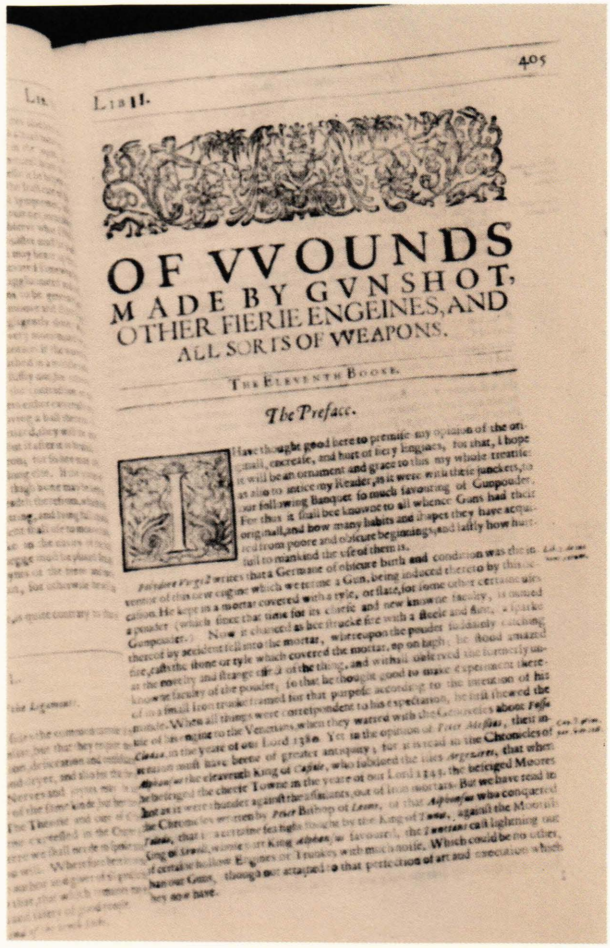
In terms of my own interests and the experience developed in the Collaborative Biomedical Program of the Applied Physics Laboratory and the Johns Hopkins Medical Institutions, the focus here will be on devices rather than materials. There is a substantial effort in both military and civilian operations to develop improved materials based on chemical and biochemical technologies, such as better temporary and permanent covers for burned areas, better plasma expanders (particularly those capable of carrying oxygen to provide adequate tissue perfusion), radiation-treated allografts and synthetics for bone replacement, improved antibiotics, and neurochemical approaches to pain relief.[21,22]

Many of the innovations to be proposed would have been impossible, at least in any portable or affordable form, a decade ago. The continuing reductions in size and cost and the increase in reliability of microelectronics for both computation and memory have revolutionized technology. Many system and device concepts that would have been considered fantasy are now low-cost reality.

We are all familiar with the basic so-called "miniature" vacuum tube and probably with the "canned" individual transistor. Compare these in size to a typical pair of modern chips (integrated microelectronic circuits). One chip may be a computational unit that can perform an addition in 2 microseconds, 500,000 additions per second; it also has a memory of 2000 eight-bit words incorporated on the chip. The other chip is a memory chip that carries 65,000 eight-bit words. Together these particular chips have the same speed and twice the memory of the 4000-tube, 10,000-diode Univac 1102 of 1956, which was the first really large computer installed at APL. The capability intrinsic today in a tiny microprocessor, requiring only a few microwatts of power, is comparable to that of the most powerful machines known to man 20 years ago, requiring 100 kilowatts and at least a 20 by 40 foot room. We thus have a capability of doing things requiring a level of complexity inconceivable a decade ago. This tremendous ability to handle computational complexity can form the basis of many different devices.

Basic Support

The problems of shelters for field use (including air quality control for surgical needs, temperature control, and transportability) and the design of transport vehicles if the helicopter can no longer be considered the primary vehicle cannot be adequately addressed here. We might, however, note one problem in the use of land transport in the Northern Ireland situation:[61] either adequate vertical height has to be provided for gravity feed of resuscitation fluids or a reversible or disposable positive pressure pump design that does not require this height has to be developed.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OF VVOUNDS MADE BY GVNSHOT, OTHER FIERIE ENGEINES, AND ALL SORTS OF WEAPONS.
The Eleventh Booke.
The Preface.

Pare's success in treating combat wounds, emphasizing sanitation and natural healing, was first reported in the 16th century. His writings, shown here in the first English edition of 1634,[7] marked the beginnings of modern surgery. Referring to the introduction of firearms into warfare, Pare comments, ". . . how hurtful to mankind the use of them is."

Electricity — Electric power for lights, pumps, sterilizers, and other equipment is essential. It will be difficult to develop a class of primary power units more efficient or more compatible with military logistics than the diesel-electric generator. Recent developments in improving automotive efficiency can be applied. Emergency reserve units that use batteries are of minimal value, although new types of batteries, particularly lithium salt batteries, provide less weight and volume and are less hazardous than the conventional lead-acid batteries. Their weight and volume still limit their utility compared to redundancy in diesel systems. However, improvements in capacity for a given size and weight and in the reliability of rechargeable batteries make many "cordless" devices now possible.

Sterile Water — Large quantities of sterile water are essential in the surgical theater. Distillation has not proven practical in the field, and sterile water has to be tanked in with the inevitable problem of deterioration of quality during storage. It would be highly advantageous to be able to produce adequately sterile water from indigenous sources. Systems using a combination of filters and membrane reverse osmosis have been adapted for many purposes and can supply large quantities of water with units of relatively small size and weight that require minimal power for an adequate pumping head through the system and have simple and relatively infrequent maintenance procedures.[101-105]

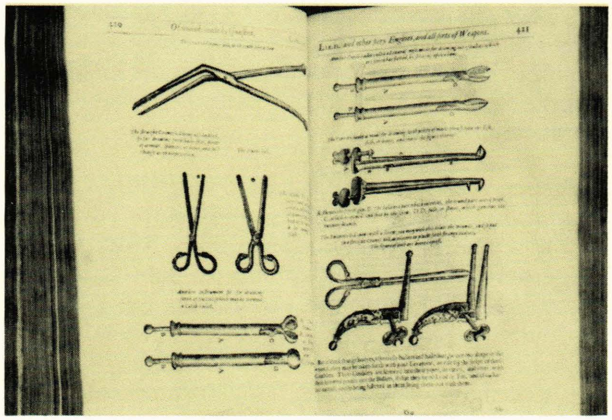
Sterilization — Steam autoclaves, heated by electricity, gasoline, or propane, are cumbersome, potentially hazardous, and energy inefficient. Properly cycled, they can provide adequate sterility.[114] Despite the increasing use of sanitary packaging of disposable items, an operating-room sterilization system is essential in the field. Systems using ethylene oxide require careful attention to procedures in order to provide adequate sterility and ensure removal of any entrapped gas in the sterile instrumentation.[107,110,111] For field use, ethylene oxide is a highly toxic material, imposing a new logistics load. However, as normally used in a 12 to 15% mixture with inert gas, it has not been hazardous to operators.

Ionizing radiation (ultraviolet, gamma, or particulates) has the problem of "shadowing," which can preclude adequate sterility in some cases. The introduction of a nuclear source may not be tolerable for field use; electric means of generation are possible, but they are fairly large and complex.[109,117,118] With adequate quantum energy, radiation can penetrate where gases cannot.

Recent developments indicate that acid glutaraldehyde combined with ultrasonic energy can be a very efficient sterilizing method.[108,119] This method introduces a new material, and fairly specific procedures must be followed to ensure proper chemical function. By itself, ultrasonic sterilization of water is not particularly efficient.

Dry heat sterilization has generated considerable interest, in part stemming from NASA processing of space probes. For materials that can tolerate it, particularly sharp instruments, heating at 180°C for 30 minutes has provided absolute sterility.[113] Since it is difficult to ensure uniform heating of air, an interesting alternative suggestion is to use a nontoxic, inert fluorocarbon with a 180°C boiling point.[116]

A systems analytic note is germane here regarding both water purity and sterilization procedures. The word *sterility* connotes a rather absolute condition of the absence of pathogens. Most military wounds are "dirty," and field conditions surrounding the injury are generally less than optimal. A careful examination of what constitutes adequacy in terms of the irreducible level of microbial matter should precede any decisions on investment in water purification or sterilizer systems. While a number of authors have discussed this point relative to the hospital environment,[106,112] I am unaware of any quantitative assessment of the military field scenario to date.



Even in the early 17th century,[7] the military surgeon's armamentarium for the removal of penetrating objects was impressive.

Imaging and Diagnostic Probes

The X ray is the basic field hospital imaging modality.[68,128] Most of the equipment available for field use today is more cumbersome and less flexible than it should be. Developments in sources, power supplies, film, and image-intensifying methods permitting short exposure (thereby also permitting less structural rigidity and the possibility of rapid equipment configuration changes) have been neither fully commercialized nor introduced into the military system.

Polaroid System — A Polaroid 10 × 12 inch film cassette system incorporating an intensifying screen is commercially available[127] and provides with high speed a positive film of apparently adequate resolution and contrast[121] within 10 to 45 seconds. This system eliminates the need for wet processing chemistry; it uses a small electrically operated processor (basically a set of rollers).

Stereoradiography — This technique was introduced in the early 1900's,[123,130] and more recently, biplanar systems that use two sources have been implemented. A simple geometric system can be developed that permits computer algorithms to provide rapid, precise location of objects in the body by use of a stereo or biplanar system. Biplanar techniques, of course, can be developed for use with a single source if the basic structure is designed to permit this flexibility.

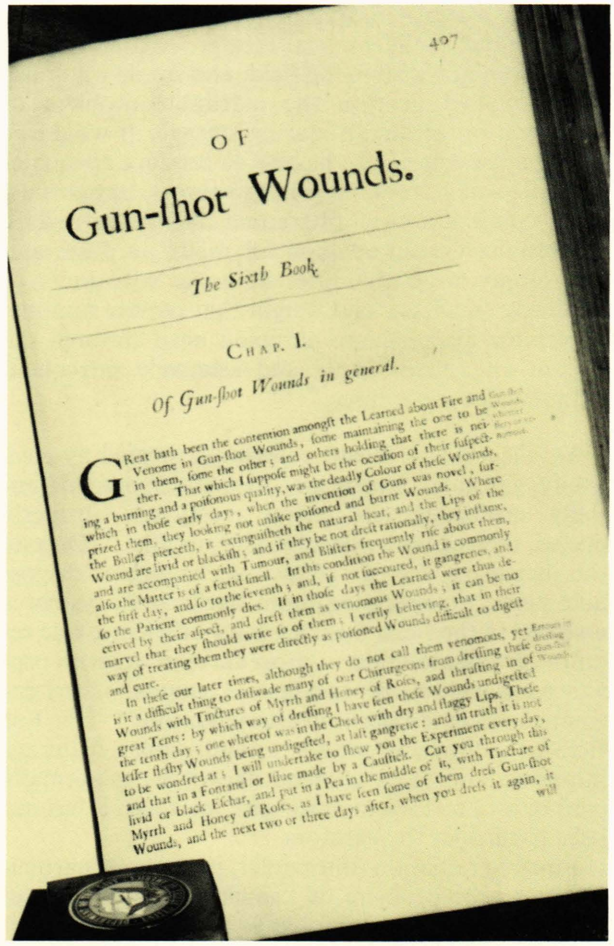
Xeroradiography — This type of radiography is an adaptation of the familiar "Xerox" concept of dry electrostatic imaging.[126] It is not clear that this technique would provide adequate improvement and capability to warrant the extra equipment, such as the processor. In general, it requires more exposure (perhaps not a significant issue in the case of military trauma). There is some possibility that the xeroradiographic image may provide better observability of nonmetallic objects.[125]

Digital Imaging — Electronic detection schemes that produce imagery can be combined with different source modalities, including scanning X-ray beams. These may afford the possibility of substantial size and weight reduction and provide greater potential flexibility, together with a reduction in radiation exposure.[124] Digital imaging can be presented on a storage screen, photographed, transformed into hard copy, or stored on magnetic tape.[122,129]

Computerized Axial Tomography — This technique (CAT scan) has become a valuable adjunct to civilian emergency medicine in the larger hospitals.[135] In general, these units involve large-scale motion of massive objects (for precise positioning) and are thus generally large and cumbersome. Civilian application for cerebral trauma has become standard when available.[132,134,138,140] Smaller-scale units have been produced, designed primarily for cerebral tomography, which has virtually eliminated cranial angiography in trauma examinations except for very special cases. Almost equivalent information can be obtained without the risk, time, or special skills required for angiography.[24] Computerized tomographic techniques have been found invaluable in trauma care for detecting hemorrhages, abscesses, and exudates in the mediastinum and abdomen.[132]

Looked at from the point of view of application of digital techniques to modern military injury, it would appear possible to reduce the mass of CAT scanners substantially by adapting digital positioning techniques. The number of approaches to developing CAT scanning electronics are legion, and I shall not attempt to itemize them here.[131,133,136,137,141] Several systems proposed or built use magnetic beam deflection and multiple-target X-ray tubes (and/or an array of multiple detectors) to minimize or eliminate the need for mechanical scan. The time for a "slice" has been reduced from minutes to a few seconds in the modern devices. Even with the large mass and size of the conventional CAT scanners intended for fixed hospital installation, several organizations have installed these scanners on standard truck trailer beds to permit sharing of the equipment by a number of hospitals.[139]

Ultrasonics — Fan-beam ultrasonic arrays, electronically or mechanically[146] scanned, have received very wide application for soft-tissue imaging, particularly in cardiology and obstetrics.[143-146] Two-dimensional imagery — a "slice" — can be provided on a screen in real time by digital processing techniques. Processing units can certainly be miniaturized. The probe itself is quite compact. This technique would appear to be particularly promising for abdominal imaging. At present, abdominal wound trauma almost invariably requires exploratory surgery because of multiple fragments characteristic of most such wounds and the frequent failure of X rays to see nonmetallic objects. Blast traumas may produce major internal lesions without any evidence of surface penetration; such lesions may be visible by ultrasonic radiography.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OF

Gun-ſhot Wounds.

The Sixth Book.

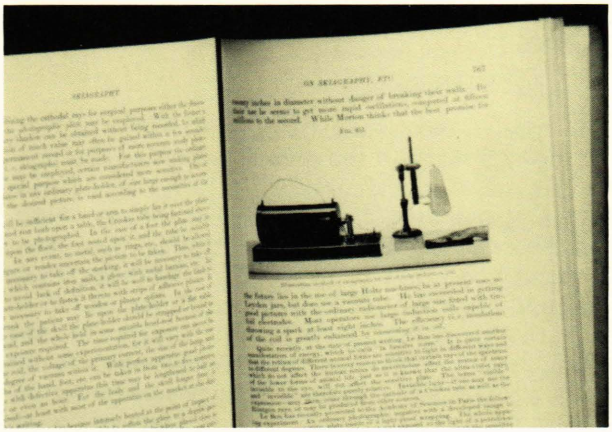
CHAP. I.

Of Gun-ſhot Wounds in general.

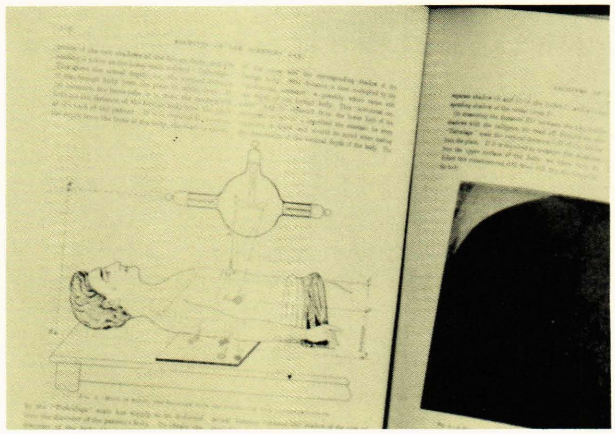
Wiseman's emphasis on surgical experience, the uniqueness of individual trauma, and the need for publication of observations as opposed to blind obedience to unconfirmed doctrine[13] began a dominant trend in trauma care extending from the 17th century to the present.

Another potential application of ultrasonics (at a higher spatial resolution level) would be to injuries of the eye and the orbit. The problem is particularly significant for blast injuries, where nonmetallic fragments may have been driven into the eye or surrounding tissue and are not observable by the usual methods and where the overpressure may have produced structural damage to the globe itself.

Ultrasonic imaging arrays cannot be readily used for imaging in the case of cerebral injury because of transmission loss through the skull. However, single-axis ultrasonic probes (echoencephalography) have been used effectively in emergency care with one-dimensional echo readings of the presence of hematoma or a midline shift.[24]



One of the earliest American articles on "skiagraphy" (X-ray imagery) by Roswell Park, *Surgery by American Authors,* Philadelphia, 1896, portrays the minimum essentials of the process: a Tesla coil, a Crooke's tube, and a photographic plate holder.



An imaginative idea for an application of X-ray imaging for locating penetrating projectiles was developed in 1909,[123] using a dual X-ray tube for stereo imaging and then calipering the distances between the image of an object in a known position and the penetrating object.

A device receiving increasing use in civilian hospitals in dealing with vascular conditions is the ultrasonic Doppler velocimeter.[24,147] This is a relatively small and compact device that measures the Doppler shift from flowing blood in vascular bodies accessibly near the surface of the body, thus determining flow rate, pulse rate, etc.

Electromagnetic Reflectometers — A number of devices have been suggested that use electromagnetic reflectometers (essentially a miniature radar system) to measure vital signs such as respiratory rate and cardiac motion. Critical applications of such devices would include determination of a casualty's condition remotely from a helicopter or armored vehicle.

Anesthesia and Analgesia

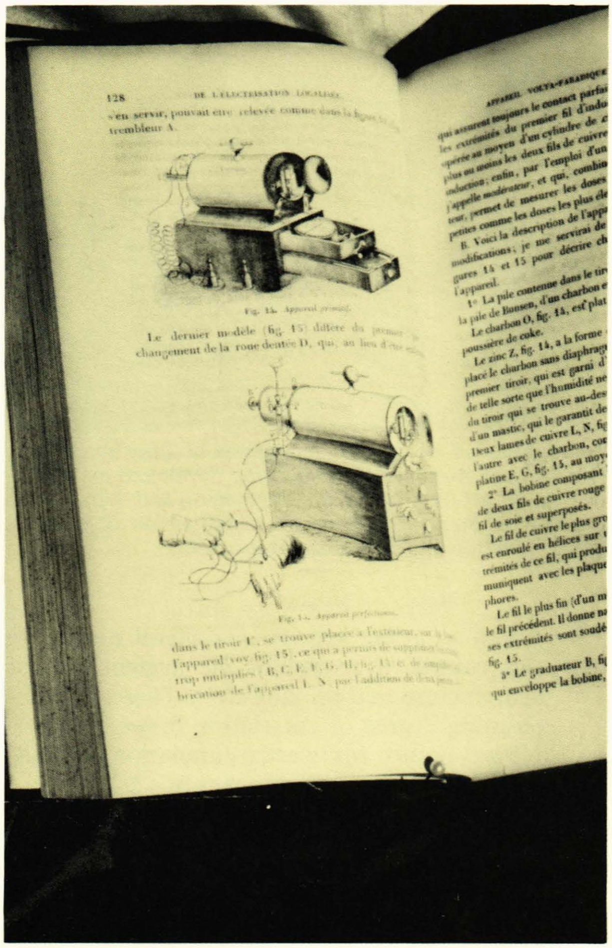
Electronarcosis, in its various manifestations, has been discussed in the literature at least as far back as the mid-19th century.[2,148,159] The reduction of perceived pain and/or the reduction in the sensitivity of perception of the environment in an individual by electromagnetic systems has been given many names, including electronarcosis, electroanalgesia, and electroanesthesia.[156,157]

As early as 1870, Althaus[148] reported attempts to produce anesthesia by electrical means and commented on the inability to do so. Leduc in 1902[161] reported the induction of sleep in dogs and himself. Wadensky, using Pavlov's concept of inhibition, produced electrosleep by pulsed currents in 1935.[162]

The various approaches to electrical stimulation[164] can be grouped into five categories:

1. Transcutaneous electrical neural stimulation (TENS)[164,168] utilizes the application of external contact electrodes so that induced currents have perhaps a somewhat diffuse effect on appropriate neural components.
2. Peripheral nerve percutaneous stimulation[163,164] involves the use of penetrating "needle" electrodes to affect specific peripheral nerves. In this regard, it resembles the ancient arts of acupuncture and moxibustion. There is an interesting degree of correlation between the effective points for electrostimulation and the traditional acupuncture locations.[153,155]
3. Electrostimulus of the dorsal column in direct response to the gate theory of pain blockage[178] has been in use since the mid-1960's.[160,163,164] Recently, epidural spinal implantation under local anesthesia, requiring simpler surgical procedures, has been accomplished.[167]
4. Stimulation by implanted electrodes in appropriate regions of the brain has proven effective in a number of conditions.[164]
5. Claims of induction of electroanalgesia by various combinations of pulsed and continuous wave radiation without either contact or implanted electrodes have been published from time to time, primarily in Soviet journals.

General electroanesthesia has been reported in a number of recent papers[151,153,154,158,166,173,176,177] involving, for example, abdominal surgery.[152] However, in all cases for which detailed reports exist, electroanesthesia was effective only after initial induction with drugs and served to reduce the number of steps and amount of chemical anesthesia required in complete induction and maintenance rather than being effective by itself. Percutaneous stimulation techniques have been found to be effective in a number of situations, in many cases analogous to the uses of local anesthesia. The TENS approach has been found effective in numerous situations requiring relief of pain,[165,171,172] most importantly, in reducing drug dosage required for postoperative pain.[149,150,170,174,175] Spinal column and cerebral implantation techniques have proven effective in a wide variety of neurological disorders and have relieved or reduced extreme chronic pain.[164,167]



After a century of random attempts at medical application and charlatanism by many practitioners, Duchenne de Boulogne became the founder of modern electrotherapy by the publication of his systematic *L'Electrisation Localisèe* in 1855.

From the point of view of field combat casualty care, the spinal column and cerebral implantation techniques require specialized delicate surgical intervention[164] and are clearly inappropriate. However, the transcutaneous and peripheral nerve percutaneous stimulation methods appear to be well worth further investigation. Our detailed knowledge of the exact neurophysiological mechanism operative in these techniques is incomplete, and statistics show that the techniques are not always effective. They nevertheless appear useful for a large percentage of patients and conditions. The possibility of producing general anesthesia in combination with preliminary drug induction may be particularly useful in certain types of trauma surgery, as would the ability to produce local anesthesia electrically. Improved postoperative condition has been reported by use of these techniques, with a reduction of atelectasis and paralytic ileus.[151,171,177] There is certainly considerable evidence that the use of TENS approach can substantially reduce the requirement for morphine-based drugs in postoperative cases, as it might well do for patients with preoperative trauma conditions awaiting surgery.

Surgical Techniques

Combat surgery since the time of Pare has been credited for many of the surgical advances that later became standard practice.[9,11,12,19] In no area is this statement more true than in vascular surgery. Anastomosis of blood vessels was successfully performed by Alexis Carrel in the early 1900's;[19] however, it was not until after World War II,[76] in Korea and Vietnam, that the techniques of vascular surgery and the training of its practitioners were developed to the point where vascular surgery became standard practice for major trauma.[77,78,79,82] For wounds of the extremities, this resulted in a tremendous increase of personnel returning to duty who, in earlier years, would have undergone amputation. A key problem remains, however, in vascular surgery under combat conditions: the requirement of specific experience and the amount of time that must be dedicated to the procedure during the surge of battle casualties.

A new approach to sutureless anastomosis[189] is under development at The Johns Hopkins University, jointly between the Applied Physics Laboratory and the Medical Institutions. This concept, based on techniques used in the aerospace industry, is very preliminary in development, but seems to have considerable potential. The method will bring together the inner layer, or intima, positively to support healing. Preliminary observations indicate that for an artery with a 3-millimeter lumen, which normally requires 20 stitches on the circumference, the time for anastomosis can be reduced to about 5 minutes from the 30 minutes required by conventional suturing techniques. Further, the ability to perform anastomosis is not inhibited by inability to rotate the vessel.

A primary factor in the success of modern combat surgery has been the practice of total debridement of nonviable tissue.[11,12] Two new technical approaches have been suggested:

1. Water jet debridement techniques,[181] developed by the U.S. Army Medical R&D, were introduced to some extent in Vietnam.
2. The use of a probe to determine the pH of tissue to distinguish the living and dead areas has been described.[180] However, I have seen no evidence of its practical development.

Additional points worth noting are:

1. Cyanoacrylate adhesives, topically applied, were successfully used to reduce intractable bleeding in a number of combat injuries[181] and were shown to be a useful substitute for sutures in special cases.[186] Concern over possible carcinogenic characteristics led to a Federal Drug Administration requirement for extensive animal testing — as it turned out, at an anticipated cost far in excess of any potential commercial profitability.[183] Thus, after 1972, commercial interest in further development ceased.

Despite some known tissue toxicity, cyanoacrylates appear to be an almost unique tool warranting further study.

2. Peripheral nerve repair[184,187] is generally not undertaken in primary surgical units.[20] However, during early wound management it is frequently essential to evaluate peripheral nerve injuries commonly resulting from high-velocity missiles and fragments. Simple techniques of evoked potential measurement *in vivo* for surgically exposed nerves have been demonstrated.[188]

Patient Monitoring

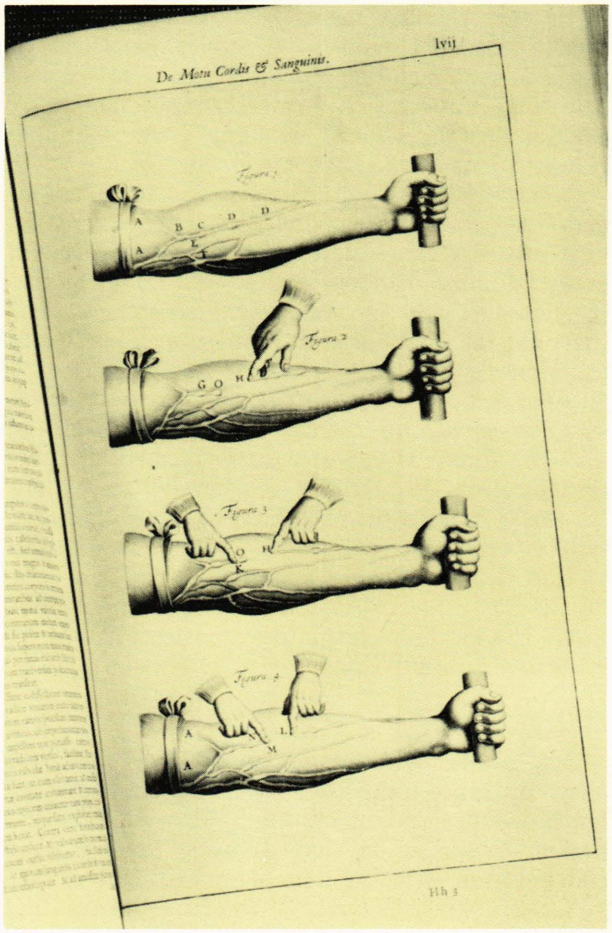
The casualty who has undergone major trauma remains at high risk for an extended period following a surgical treatment. This potential of risk will be severely increased as a function of the delay time between wounding and surgical treatment and of the related problem of how well balanced the maintenance of body fluids and electrolytes was during the transit phase. In Vietnam and other recent conflicts, in situations where the helicopter reduced transit times to the order of one to two hours, the number of patients who underwent acute renal failure (one in 600 in Vietnam; one in 200 in Korea) or acute pulmonary insufficiency — particularly in cases of thoracic injury — was remarkably small compared to the number that would be expected if the delay time stretched to 10 to 15 hours, typical of land transportation methods.[85-88]

Certain key body parameters must be continuously monitored in order to alert medical personnel to, or to provide treatment to reduce risk of, the imminent occurrence of acute pulmonary insufficiency or acute renal failure. These include:

1. Blood gas analysis, particularly pO_2 and pCO_2, as well as blood pH;
2. Hemoglobin and hematocrit;
3. Serum and urine factors, such as Na, K, Ca, Cl, CO_2, and osmolality.

In the last decade, automated techniques giving direct reading units for blood (or other fluid) samples have been produced for the laboratory and hospital. Compact systems, capable of withstanding military rigors, can almost certainly be developed to measure most of these parameters rapidly and simply and, in some cases, continuously "on line."

A critical parameter in any case of cerebral injury, most particularly those without penetration wounds such as might be assumed in many blast victims, is intracranial pressure.[202] Continuous measuring of the intracranial pressure is a problem for many conditions other than trauma. A recent development at The Johns Hopkins University,[196,197,205] quite successful in experimental clinical practice, is the "pressure pill"; this is a small passive device, essentially a mechanical diaphragm coupled to an electronic transducer, that can be inserted into a small burr hole and allowed to remain in the skull. For chronic conditions, the skin flap can be resutured. The pressure



William Harvey's explanation of the dynamics of blood circulation[4] marked the beginning of modern physiology and paved the way for rational treatment of massive trauma.

can be read out by a simple external probe that is electromagnetically coupled to the electronic transducer, thus permitting continuous reading of intracranial pressure without physically attaching any device to the patient.

A significant and common problem in the treatment of patients suffering extensive burns is the development of Curling's ulcer. There appears to be some correlation between this syndrome and gastric hypersecretion.[90] At The Johns Hopkins University, a portable pH data detector has been developed[204] that monitors gastric secretion by a sensor tubulation into the stomach, permitting continuous readout by a small computer/recorder that can be attached to the patient.

When the patient is in a responsive state, a useful set of techniques for determining the amount of, or the change of state of, neurological injury is reaction timing. Various combinations of signals, either audio or visual, that require a "button-pushing" response can be provided to the patient. A memory can be provided of the patient's performance at any given time for automatic comparison so that changes can be observed. A recent program of The Johns Hopkins University has produced a pocket-computer-sized version of a reaction timer.[199] Without a particular increase in size, it can be developed into a device capable of matching any of the more complex laboratory reaction time procedures, including retention of individual patient characteristics in its memory.

Generally, the casualty victim who has undergone major surgery for trauma is for some time thereafter in an intensive care situation requiring monitoring of a large number of body parameters.[190] This implies substantial loads in manpower, equipment, and space for the field hospital. Modern microelectronic techniques can be applied to provide extremely miniaturized equipment that can be attached to, or otherwise associated with, the individual patient. Further, the existing knowledge of pattern-directed inference systems can be applied to develop automatic systems[195] to alert the physician to a rapid change of state as a dynamic function of a patient's condition: an "artificial intelligence" approach of logical combination as expressed in computer software or firmware. This has been clinically demonstrated[203] for the acute phase of burn cases.

Patient Support

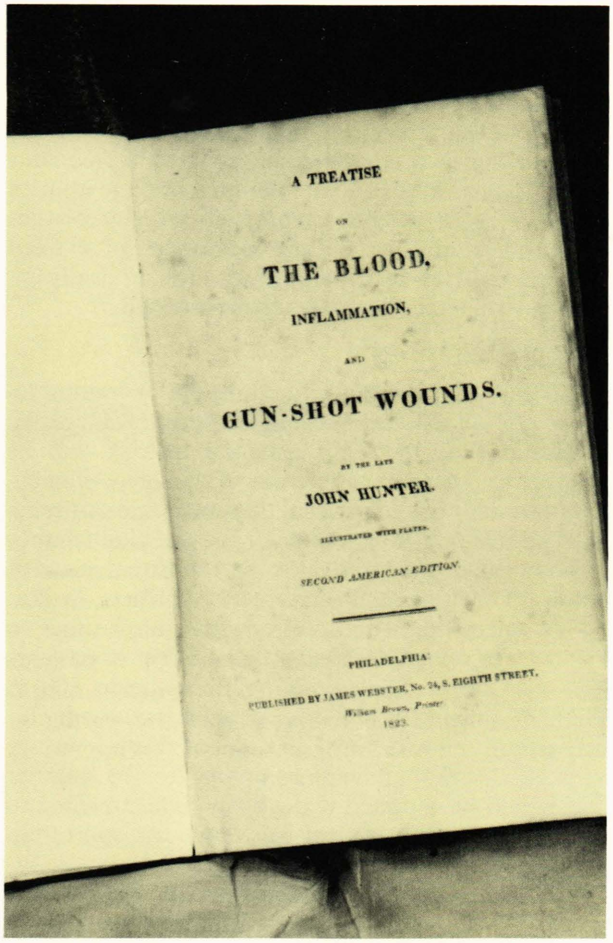
During the past decade, an extensive program based on space technology to develop miniaturized implanted devices for chronic patient support has been under way at the Applied Physics Laboratory in collaboration with the School of Medicine at The Johns Hopkins University. Implant devices and space satellites have several features in common:

1. The need for near-absolute reliability because they cannot be reached for maintenance,
2. The need to determine remotely the operational status of the system,
3. The need to change functional parameters by remote means.

Modification of devices developed for chronic implantation to provide patient support for cases of military trauma appears to be an attractive possibility. What is proposed here is to adapt these devices for external attachment to the patient. These devices are totally self-contained: they use internal power sources, either long-life lithium batteries or inductively rechargeable NiCad batteries. Microprocessors internal to the device can be programmed for complex functions, with changes in program being possible through a programmed electromagnetically coupled computer concept.

Following the initial development of rechargeable heart pacemakers, a number of substantially more complex devices have been developed and clinically tested or are now in the final stages of development. These include:

1. Automatic Implanted Defibrillator.[200,201] This device can sense the onset of fibrillation, charge a capacitor from its battery, and apply up to three defibrillating impulses to internal electrodes. The design of an advanced device[193] will include adequate memory to permit the physician to read out the time history prior to the onset of fibrillation, and it will provide sensible warning of the onset of fibrillation.
2. Programmable Implantable Medical System.[191] Initial application is directed primarily toward timed release of insulin for diabetes, an "artificial pancreas." The device includes full programming schedules, redundant safety interlocks, a drug reservoir, and a miniaturized pumping unit for release of the drug. The device currently assembled is designed for an approximately 10-year life, with a lithium battery; for the average diabetes patient who requires insulin, it would be recharged with fluid once every three months by hypodermic injection. A wide variety of other applications, including local administration of drugs for a variety of different diseases, for analgesia,[192] or for chemotherapy, are envisioned.
3. Implantable Neurostimulator. Notable successes in the use of electrostimulation for local



The development of experimental surgery and modern pathology in the 18th century is associated with John Hunter. His teachings[5] were the dominant influence in the care of the wounded on both sides of the American Revolutionary War.

analgesia or reduction of neurological impairments have been discussed. The Hopkins device[167] uses a rechargeable battery and can supply 2×10^8 combinations of two pulses, varying in voltage, pulse width, pulse separation, etc. The device is implantable, with leads placed to the appropriate neural points for stimulation of brain regions, the spinal dorsal column, or peripheral nerves.

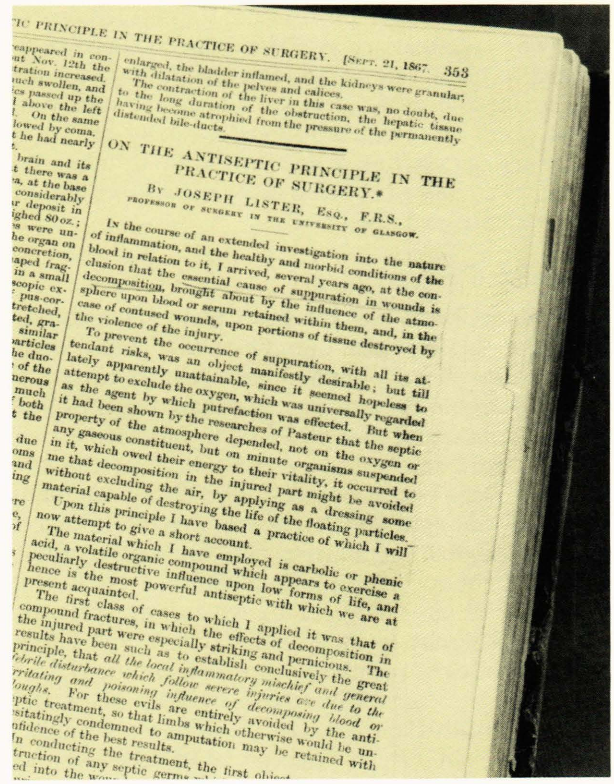
All of the above devices are about the size of small modern implantable pacemakers. Each is capable of having an "electronic prescription" programmed in by the physician.

Extrapolation of possible future contingencies in casualty care suggests a number of other possibilities.

1. In the event of extensive delay in transport, a larger number of acute renal failure cases could be anticipated. It is quite possible that individual miniaturized dialysis units could be developed.
2. During the past decade, a considerable number of developments have occurred in mechanical ventilatory support systems,[24] which should be examined for potential military use, particularly in the case of post-traumatic pulmonary insufficiency. One major advance in respiratory therapy is the use of positive end expiratory pressure. Another important development has been the intermittent mandatory ventilator, which can serve in the transition period prior to removal of mechanical support. The patient can remain attached to the ventilator and spontaneously breathe the gas mixture, with the machine delivering predetermined volumes of gas at chosen intervals.
3. Recent developments in fiber-reinforced epoxy materials have led to extremely rigid, strong, and lightweight materials that might be applicable to fracture management. This material was used in the MAGSAT satellite built at APL for precise measurement of the earth's magnetic field and requiring extended separation of the magnetic sensor from the satellite body while maintaining extremely precise positions.
4. With the possibility of conflict in areas of extreme cold, handling of wound trauma and extremity exposure trauma brought about by cold requires compact, energy-efficient local heating. Consideration should be given to electromagnetic radiation devices with an appropriate range of frequencies for maximum coupling to the part of the body involved.

Patient Data

Starting with initial first aid, the casualty moves from echelon to echelon with different, generally noncommunicating, individuals at both the physician and the technician levels. Retention of precise data on both therapy and trauma observable in different periods is essential.[21] The retained data should start


ТIC PRINCIPLE IN THE PRACTICE OF SURGERY. [SEPT. 21, 1867. 353

enlarged, the bladder inflamed, and the kidneys were granular, with dilatation of the pelves and calices.

The contraction of the liver in this case was, no doubt, due to the long duration of the obstruction, the hepatic tissue having become atrophied from the pressure of the permanently distended bile-ducts.

ON THE ANTISEPTIC PRINCIPLE IN THE PRACTICE OF SURGERY.*

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IN the course of an extended investigation into the nature of inflammation, and the healthy and morbid conditions of the blood in relation to it, I arrived, several years ago, at the conclusion that the essential cause of suppuration in wounds is decomposition, brought about by the influence of the atmosphere upon blood or serum retained within them, and, in the case of contused wounds, upon portions of tissue destroyed by the violence of the injury.

To prevent the occurrence of suppuration, with all its attendant risks, was an object manifestly desirable; but till lately apparently unattainable, since it seemed hopeless to attempt to exclude the oxygen, which was universally regarded as the agent by which putrefaction was effected. But when it had been shown by the researches of Pasteur that the septic property of the atmosphere depended, not on the oxygen or any gaseous constituent, but on minute organisms suspended in it, which owed their energy to their vitality, it occurred to me that decomposition in the injured part might be avoided without excluding the air, by applying as a dressing some material capable of destroying the life of the floating particles.

Upon this principle I have based a practice of which I will now attempt to give a short account.

The material which I have employed is carbolic or phenic acid, a volatile organic compound which appears to exercise a peculiarly destructive influence upon low forms of life, and hence is the most powerful antiseptic with which we are at present acquainted.

The first class of cases to which I applied it was that of compound fractures, in which the effects of decomposition in the injured part were especially striking and pernicious. The results have been such as to establish conclusively the great principle, that *all the local inflammatory mischief and general febrile disturbance which follow severe injuries are due to the irritating and poisoning influence of decomposing blood or sloughs.* For these evils are entirely avoided by the antiseptic treatment, so that limbs which otherwise would be unhesitatingly condemned to amputation may be retained with confidence of the best results.

In conducting the treatment, the first object

Lancet, in 1867, published Joseph Lister's classic series of six papers announcing the successful use of antiseptics for the surgical treatment of wounds. The techniques of Pare, Hunter, and Lister laid the foundations for 20th century surgery.

initially with very simplified information on treatment applied at the corpsman level and gradually build up as primary and definitive surgical care is applied. The high reliability, low cost, and intercommunication possibilities of modern computer systems should make data collection and retention relatively simple to effect. At The Johns Hopkins University, a number of clinical information systems of various degrees of complexity have been developed, ranging, for example, from a highly simplified system that produces a minirecord for the outpatient clinics[206] to a relatively detailed tertiary-care patient management system for the oncology center[207] that provides complex therapeutic protocols.[208]

Perhaps the most exasperating part of information retention and processing has been the initial casualty tagging problem. One suggestion[209] that may substantially reduce the psychological problem of note-taking under pressure and retention of legibility is to equip the first echelon with a miniaturized tape recorder containing two tapes: one would be a "read-only" tape, containing a structured query with some branching capability, and the second would be a "write-only" tape to record responses. The miniaturized tape cassette containing the "write" record can be attached to the patient and added to and/or read out at successive levels of treatment. Simplified transcription systems using word processing techniques could produce an accurate transcribed record that, when services are available, can be telecommunicated to further points in the evacuation chain and to a permanent data store. An automated data base could result that would support casualty reporting and training. Definitive identification through the computer chain can be retained by use of appropriate service identification numbers.

Automated Triage

Triage decisions can be both difficult and emotional for the physician and even more so if they have to be made by the corpsman. They occur iteratively at several points in the casualty care chain and are absolutely necessary to optimize the application of resources, particularly the available time of the surgeon. During the last decade, there have been many programs designed to use pattern-directed inference systems, both for diagnosis and for therapy guidance.[190,198] Many computer algorithms have been proposed, a small number of which have been directed specifically to the question of triage at different levels of care, primarily for trauma in the civilian environment. Faced with the possibility of limited transportation resources, the inevitable multiplicity of casualties in a short time typical of combat situations, and probable dispersal of third-echelon resources to minimize their targetability, the critical points of triage decision-making are:

1. The initial corpsman decision as to whether to evacuate the casualty, to determine whether to bypass second-echelon facilities, and, in some cases, to decide whether to transport the patient to a known specialized facility;
2. The classical triage area where decisions have to be made about who requires care most urgently, which aspect of care takes priority, who can wait, and who can only be made comfortable when further expenditure of resources is futile;
3. In the postoperative phase, determination of the probability of survival and time and direction of further evacuation and care.

Computerized decision aids could assist in a personnel-limited situation for determining the course of therapy; many proposed and, in some cases, clinically evaluated concepts have been described.[198] A more limited number of systems have been postulated for the triage problem:

1. By use of a triage index characterizing initial patient status[217,218] with regard to central nervous system function, respiratory function, and blood loss, a noninvasive system, based on Bayesian probability and capable of use by paramedics, has been proposed. The three clinical conditions related to early death are assumed to be profound respiratory distress, hemorrhagic shock, and unconsciousness. Observations would include eye opening, response to voice or pain stimuli, level of orientation in verbal response, simple motor responses, capillary refill, and respiratory expansion.
2. Another approach[211] uses an "injury severity score" based on the "abbreviated injury score" developed by the Committee on Medical Aspects of Automotive Safety.[213,214] The injury severity score is defined as the sum of the squares of the highest abbreviated injury score grade in each of the three most severely injured areas of the body. Analysis indicates that death rates increase in the presence of injuries involving two or three body areas, even if the individual injuries in themselves are not necessarily life-threatening. This quadratic summing of abbreviated injury score ratings correlates with death rates from auto injuries substantially better than abbreviated injury score values themselves.
3. A prognostic index for severe trauma, using specific physiological and biological measurements, has been developed based on six parameters measured in initial survivors who had arrived at emergency medical facilities.[215,216] Originally 12 parameters were chosen. However, the actual survival compared to the initial prognosis was found to be sensitive to systolic blood pressure, hematocrit, fibrinogen, potassium, serum osmolality, and creatinine. The computer algorithm used provides a single number, the "Euclidian distance," in a vector phase space, which relates to the six stated variables relative to the average value of the parameters of patients who survive.

Again, microprocessors should permit the development of pocket-computer-sized systems containing the algorithm appropriate for the paramedic in the field or the physician or nurse in the surgical situation. These algorithms, in turn, should permit the introduction of the real-time-situation parameters, i.e., backup in transportation, surgical time available, and special care facilities available, so that the triage separation levels are appropriate to the actual situation.

Communications

Casualty care services should make more use of modern communications capabilities:

1. Voice bandwidth communications for consultation with specialists at remote locations are essential. Even with relatively narrow bandwidth, it is possible, using modern digital imagery technology, including long-persistence tubes and slow-scan TV imagery (in color if needed), to transmit visual information about patient and trauma conditions.
2. Access to a functionally structured data base in order to provide textual information for remote reference could be a valuable adjunct in the field.

A major effort is under way in all services to improve their communications systems and to solve problems of priority, survivability, and saturation. Command and control obviously will always have the top priority. If a medical communications system is instituted, it must be included in the overall communications architecture of its service as early as possible. This requires careful analysis of circuit interconnections, modes of communications, volume of communications, etc. Additionally, since much of the system adopted for data recording and information access will involve computer formats, computer compatibility must be established throughout the system.

High-Technology Equipment Quality Assurance

Last, but not least, if increasing amounts of high-technology devices and systems are introduced in the military system, the devices and systems themselves must have their own health care system to ensure effectiveness, safety, and availability for patient use. APL, together with the Johns Hopkins Hospital, has developed a low-cost, readily maintainable, computer-based documentation system.[210] This current computer inventory includes 4800 items in 16 clinical functions, together with their associated laboratories. The computer-based data include:

1. Acceptance testing information,
2. Records of the need for calibration and preventive maintenance and their accomplishment,
3. Identification of key personnel concerned with the use and maintenance of the equipment,
4. Data on performance of a given piece of equipment,
5. Data on utilization of a given piece of equipment.

CONCLUSION

The system we seek to improve has two immediate goals: preservation of life and relief of stress. In these processes, the possibility of subsequent damage to the individual has to be minimized within the constraints of the field environment. The primary object is to return the man to his post as rapidly as possible or, if this cannot be done, to reduce the probability of permanent impairment.

A brief survey has been presented of some possible applications of new technology; some may turn out to be more useful than others, some more capable of being acquired and implemented than others. Some items not applicable in the field may find application aboard ship.

With the caution that the apparent desirability of any single innovation has no meaning unless it is inserted into, and evaluated with, a model of the overall casualty care system, a simplistic model can be proposed for a first-order assessment of the potential value of any given device or technique. The value could be considered as having four components in a four-dimensional phase space: the vector sum (i.e., the square root of the sum of the squares) of the components. Ordering the scale of values for each axis from high to low:

1. The first coordinate axis is Significance: (a) a major new and significant capability; (b) an improvement of existing capabilities — faster or lighter or more reliable or cheaper, etc., or some combination thereof; (c) a capability that would be nice to have.
2. The second coordinate axis is Utility: (a) general-purpose utility for combat surgery; (b) very useful for severe but not uncommon complications; (c) specialized occasional need.
3. The third coordinate axis is State of the Art: (a) technology now used in the civilian world directly adaptable if militarized to the extent required; (b) a technological solution to a biomedical problem of possible interest with a different approach to the military need; (c) technology that has been well developed for other purposes with potential interest.
4. The fourth coordinate axis is Effort Required: (a) minimal development required to achieve militarily applicable devices; (b) significant development required, but with high probability of achievement; (c) technical complexity or uncertainty, a rather exploratory, even "researchy" project.

Obviously, evaluating each (perhaps at first glance desirable) device for its proper values in this model is a highly interdisciplinary task, requiring technologists and physicians to talk to each other.

It might be noted that cost *per se* is not considered a component of the model (although reflected to some extent in the fourth axis, "Effort Required"). Investment decision is usually a trade-off among effectiveness, cost, and time. In terms of the magnitude of costs for weapons' hardware and maintenance of forces in peacetime (and much more so in wartime), any potential cost involved in biomedical acquisition is relatively trivial. The trade-off of primary interest here is effectiveness versus time. In this sense, it should be easier to develop and experiment with new technologies in peacetime. A point of caution is that with complex military systems it is difficult to field a new system in less than eight years between the decision to go ahead and a serial production level adequate for introduction in the field. The wartime record has been somewhat better. During time of war, bureaucratic impediments to development are reduced (thus shortening development time), cost consciousness is minimal, and high risk for high gain is a desideratum.

Another important caution is not to depend on commercial initiative for the development of new biomedical technologies for military use. Long, sad, and economically inevitable experience in the biomedical field has been that commercial initiative is not a function of utility; rather, it is a function of profitability, more specifically, return on generally limited investment.

It has been difficult in the past to obtain adequate funding and management resources for new biomedical developments. However, a carefully developed analysis of a total system requirement can gain the support of military decision-makers. Military medicine has many unique areas, as well as many prosaic areas supplying conventional medical care. There is no question, however, that the *raison d'être* of the military medical services is combat casualty care. As the distinguished surgeon and historian, Owen Wangensteen, stated: "Surgeons have always been appreciated by military leaders."[12]

Preparing for the care of combat casualties resulting from the next unknown, but probably inevitable, conflict may be disquieting. A comment of John Hunter in the 18th century seems appropriate:

> . . .It is curious to observe, that firearms and spirits are the first of our refinements that are adopted in uncivilized countries; and, indeed, for ages they have been the only objects that have been at all noticed or sought after by rude nations.[5]

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The following references should not be considered either definitive or comprehensive. They represent various materials the author found helpful and readily available in preparing this particular paper. For the convenience of the reader (and the author), the material has been broken down into subject headings with some degree of approximation to the order of the text. The entries preceded by an asterisk are bibliographic entries and have not been cited in the text.

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