

Biology and the Battlefield

by Robert E. Armstrong and Jerry B. Warner

Overview

The military and the life sciences have been intertwined throughout history. Biology has often been a source of offensive weapons, ranging from the hurling of plague victims over the walls of Kaffa (which probably started the 14th-century Black Death) to the anthrax attacks of fall 2001.

The military-biology relationship also has a humane side. Over the years, medical advances have saved countless soldiers and contributed to the overall well being of society. From the smallpox inoculation of Continental Army recruits in 1777—nearly 20 years before Edward Jenner's smallpox vaccination—to the development of modern vaccines, military physicians have a lengthy and impressive record of achievements.

Biology has a new military role in the 21st century. Using the tools of biotechnology, the emphasis is now on increasing warfighting capabilities by improving matériel and enhancing warrior performance. Potential new tools range from small electronic devices based on bacterial proteins to foods that contain vaccines. The possibilities range from warriors functioning without difficulty in extreme environments to unmanned aerial vehicles flying in autonomous swarms.

For the military to benefit fully from the advances of 21st-century biology, a new organization is needed within the Department of Defense (DOD) that addresses the ethical, legal, and regulatory implications of biotechnology. This entity also must ensure that DOD biotechnology spending is increased and that the majority of the funds are directed to warfighting issues rather than the longstanding biological concerns of medical and defensive measures.

A Brief History of Biology and the Battlefield

There was a time when mention of the words *biology* and *military* in the same sentence conjured images of biological warfare agents laying waste to soldiers and civilians alike. Some medical historians suggest that the plague pandemic of the 14th century was due to military actions in 1346, when the dead bodies of plague victims

were thrown over the walls of the besieged Black Sea port of Kaffa. The Russians employed a similar strategy in 1710, provoking an epidemic among their Swedish enemies. By 1767, the agent of choice had shifted to smallpox. Some historians say that during the French and Indian War, English General Lord Jeffrey Amherst supplied smallpox-infected blankets to Indians loyal to the French. The resulting epidemic played a significant role in Amherst's capture of Fort Carillon, which he renamed Fort Ticonderoga.¹

By the beginning of the 20th century, the germ theory of disease was well established, and potential victims extended beyond the human population. During World War I, at least two instances are well documented of German agents trying to infect horses destined for use by U.S. troops in Europe. Operating in the United States, German agents unsuccessfully inoculated horses with glanders disease—a fatal bacterial disease that can also infect humans—prior to their shipment to Europe.² In January 1917, Baron Otto Karl von Rosen was apprehended in Norway on suspicion of espionage and sabotage. His luggage contained a sealed glass tube, later determined to hold anthrax. His plan was to put the bacteria on sugar cubes and feed it to horses carrying supplies to the Allies.³

During World War II, the infamous Japanese Unit 731 conducted experiments with a broad range of agents, including anthrax, tularemia, plague, botulism, smallpox, glanders, typhoid, and typhus. Prisoners were used as subjects in many of the experiments, and reports show that about 1,000 autopsies were performed on anthrax victims. In 1940, the Japanese succeeded in causing a plague epidemic in China and Manchuria. They airdropped bags filled with plague-infected fleas and grain. The grain attracted rats, which then carried the infected fleas to humans.⁴

During the 1970s and early 1980s, the Soviets were suspected of various biological misdeeds in the pursuit of their national interests. Aerosols sprayed from helicopters in both Southeast Asia and Afghanistan were thought to be acts of biowarfare. While the so-called Yellow Rain sprayed from the aircraft was never definitively proven to be a biowarfare agent, there is strong suspicion that it was a mixture

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE MAR 2003		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Biology and the Battlefield				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Defense University Center for Technology and National Security Policy Fort McNair Washington, DC 20319				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

of mycotoxins—toxic materials derived from fungi. The case of Bulgarian exile Georgi Markov is well documented, however. Communist agents stabbed Markov with the end of an umbrella in London, and he died several days later from ricin poisoning. (Ricin is a toxic material derived from castor beans.) In 1979, the Soviets lost at least 40 of their own citizens in Sverdlovsk to an outbreak of anthrax, which initially was declared a natural event. In 1992, President Boris Yeltsin confirmed that the deaths were actually due to an accident at a nearby military compound that was experimenting with anthrax.⁵

In the late 1980s and early 1990s, a more widespread picture began to emerge of state-sponsored biological warfare efforts. Defectors from the former Soviet Union told of genetically engineered “superbugs” that included antibiotic-resistant anthrax and more virulent forms of plague. Some of the reports claim that the Iraqis succeeded in weaponizing anthrax, botulinum toxin—causative agent of botulism—and the mycotoxin aflatoxin. It has also been reported that the Iraqis loaded some of their Scud missiles with biological agents.⁶

The idea of the battlefield has changed over the years, and the September 11 attacks and subsequent events clearly demonstrate that warfare need not be confined to two armies arrayed on a field of battle. In fact, the first documented case of bioterrorism in the United States took place in restaurants. In 1984, followers of the Indian guru Bagwan Shree Rajneesh sprinkled salmonella on salad bars throughout a rural Oregon county. More than 750 cases of food poisoning resulted, with 45 hospitalizations. In the early 1990s, followers of the Japanese Aum Shinrikyo cult tried as many as 10 times to release botulinum toxin and anthrax in Tokyo. (Although all of their biowarfare attempts were unsuccessful, they did conduct a lethal chemical attack using sarin gas in a Tokyo subway, resulting in 12 deaths in 1995.) Most recently, a still unidentified individual or group mailed anthrax-laden letters to media and political personnel in the United States, resulting in five deaths.⁷

While the use of bioterrorism has added new dimensions of horror to war, not all of the connections between biology and the battlefield have been destructive. In fact, using biology as a means to save, not end, lives has long been a focus of global armies. The history of the U.S. Army alone is replete with biomedical advances that have not only saved countless lives of soldiers but also resulted in major improvements to public health. For example, in 1777, George Washington had all Continental Army recruits undergo inoculation against smallpox, a bold step for the time. Army doctors continued to make advances during the Revolutionary War. In 1778, they published the first American pharmacopoeia, a 32-page list of medications. In 1779, Army surgeon James Tilton built a well-ventilated hospital, complete with isolation wards, which influenced the design of hospitals for decades.⁸

The next century saw additional medical contributions from the Army. In the early 1800s, William Beaumont observed and described the gastric digestion process in a patient whose abdominal

wound never fully healed. His 10 years of observation resulted in the publication of a book that became the cornerstone of modern gastroenterology. Later in the century, with further advances in scientific methods and apparatus, Army doctors developed the first methods for taking microscopic photographs of bacteria.⁹

As American forces engaged in operations worldwide, the problems of endemic diseases became important to the military, and a host of Army doctors made significant discoveries. Lieutenant Bailey Ashford, for example, demonstrated that hookworm caused “Puerto Rican anemia,” and his treatment and control methods benefited both the civilian and military. Major Walter Reed became world famous for his conquest of yellow fever. Lieutenant Charles Craig and Captain Percy Ashburn proved that dengue fever was viral. Captain Edward Vedder demonstrated that partially milled rice prevented beriberi, and Major Frederick Russell developed an antityphoid vaccine. Major Reuben Kahn developed a blood test for syphilis that was the diagnostic standard for years. Captain Fernando Rodriguez isolated the bacteria responsible for tooth decay and laid the basis for modern preventive dentistry. Major Raymond Kelsner, an Army veterinarian, developed vaccines against rabies and rinderpest, and, as recently as 1970, Colonel Trygve Berge was credited with developing a vaccine that stopped the spread of Venezuelan equine encephalitis—dangerous to both humans and horses—from Mexico into the United States.¹⁰

That Was Then, This Is Now

These examples show that until the last decade or so, the connection between biology and the battlefield was largely about the medical and biowarfare aspects of biology. The new emphasis is on how biology can be used to enhance our capabilities to conduct military operations: not by degrading our adversaries, but by improving the matériel of war, enhancing the performance of warriors, and using biological processes to improve systems design and performance.

The language of 21st-century biology has become commonplace in the media. Articles routinely appear in which deoxyribonucleic acid (DNA) is discussed, as well as all of the intricacies of genetic engineering. A short review may be helpful.

A gene is a given strand of DNA that contains the instructions for manufacturing a particular protein. The previous belief held that one gene had instructions for one and only one specific protein. Data from the human genome project, however, indicate that the entire human genome—that is, the full complement of genes that we possess—consists of about 30,000 to 40,000 different genes. A typical cell makes hundreds of thousands of distinct proteins. Moreover, although all cells contain the same complement of genes, cells are specialized and do not all manufacture the same proteins. Thus, the study of the full complement of proteins—proteomics—is considerably more complicated than genomics and offers a rich array of molecules that can potentially enhance military operations.¹¹

Proteins come in a variety of shapes and sizes and perform a myriad of functions. They are the building blocks for our bodies—our hair, our fingernails, and the cells lining our lungs are all made from specific proteins. Other proteins act as enzymes to mediate the many biochemical reactions that take place in our bodies every day. The firing of nerve cells, the contractions of muscles, the digestion

Robert E. Armstrong is a senior research fellow in the Center for Technology and National Security Policy at the National Defense University. Dr. Armstrong may be contacted via e-mail at armstrongre@ndu.edu or by phone at (202) 685-2532. COL Jerry B. Warner, USA (Ret.), is president of Defense Life Sciences. COL Warner may be contacted via e-mail at warner@dlsci.com or by phone at (703) 725-2482.

of food, to cite just a few examples, are all processes mediated by proteins specific to a given function.¹²

Proteins are made of amino acids arrayed as if on a chain. While there are hundreds of thousands of proteins, there exist only 20 amino acids. The particular amino acids used, as well as the sequence, determine which protein is manufactured.¹³ Proteins have unique folding characteristics that help define their functions. If a protein does not assume the proper shape after the amino acids have been assembled in the proper sequence, then it will not function.¹⁴

The revolutionary advance in modern biology that marked the end of the 20th century was the development of the ability to cut genes out of one species' genome and then transfer them to that of another. The transferred genes function as if in the original species and manufacture unique proteins. For example, the genes for manufacturing insulin can be taken from the human genome and transferred to a common bacterium (*E. coli*). The genes function inside the *E. coli* and manufacture human insulin. Since human insulin is not something used by the bacterium, it is excreted and can be economically collected for human use.¹⁵

In a 2001 report released by the National Research Council (NRC) entitled *Opportunities in Biotechnology for Future Army Applications*, the authors noted the shift from classical approaches in biology to the current genomic and proteomic approaches:

Classical approaches to the study of biology have involved biochemistry (the study of proteins in isolation) and genetics (the study of individual genes in isolation). But the examination of an entire genome and its products, a relatively new subdiscipline known as genomics (the study of the genetic material of life), may unlock the secrets of the communication, structure, organization, and interaction of cells and molecules and how they create function. The long-term implications of genomics will present the Army with opportunities and challenges even in the next decade. . . . Proteomics complements genomics by bridging the gap between genetic message and protein-expression levels.¹⁶

So what militarily relevant things may be possible with this new biology? Following is a brief survey, mostly condensed from the 2001 NRC report, of some promising areas that will likely come to fruition in the near to midterm.

Electronics

Soviet scientists completed much of the early work on protein-based electronic devices during the Cold War, in an effort to jump ahead of Western computing technology. Although much of the results of their efforts remain classified, their work on bacteriorhodopsin has become widely known. Bacteriorhodopsin is a good example of a protein that can be adapted for military purposes and illustrates the potential for such an approach.

Bacteriorhodopsin can be isolated from the bacterium *Halobacterium halobium*. *H. halobium* is an extremely old bacterium, in an evolutionary sense, having been around for about 3.5 billion years. It is well adapted to harsh environments, can live in salt marshes, and survives at temperatures as high as 140 degrees Celsius. It also functions well in intense light. Such characteristics would be ideal for many components of military hardware. Instead of trying to build an electronic device to meet such operating requirements, a better approach might be to adapt something that has withstood eons of

evolutionary selective pressure and been thoroughly field-tested for its operating efficiencies. Why not adapt bacteriorhodopsin?

When struck by light, bacteriorhodopsin undergoes a predictable series of shape changes. Each intermediate step in the process has unique spectral properties that can be exploited for use in an electronic device, making the protein multifunctional from a design engineer's perspective. Also, bacteriorhodopsin mutants have been genetically engineered specifically to improve the protein's performance for selected purposes. For example, the mutants can yield greater quantities of particular shapes of bacteriorhodopsin or can yield proteins that hold desired shapes for extended periods of time.

Work on protein-based electronics covers an array of devices with several military and civilian applications. Holographic and three-dimensional memory devices have particular utility for the military. Future plans call for each soldier to be outfitted with a wearable computer system to provide situational awareness displays, analysis of sensor and targeting data, and communications. One such prototype device, using bacteriorhodopsin, can store 7 to 10 gigabytes of digital data in a 1-centimeter (cm)-by-1-cm-by-3-cm polymer vial, capable of withstanding virtually any environmental abuse, including extended submersion in water. (By comparison, a typical personal computer comes with a storage capacity of 20 to 40 gigabytes.) The holographic properties of bacteriorhodopsin can be further exploited for the design and manufacture of associative memory devices. Such devices take an input data block and scan it against stored images. One practical military application is for the rapid battlefield identification of friend or foe (IFF).

Closely related to associative memory devices are pattern recognition systems. A pattern recognition device, employing genetically modified bacteriorhodopsin, is already used commercially for detecting counterfeit currency. The 2001 NRC report recommended the Army use such a system for target identification and IFF.

Other bioelectronic devices in the offing include hybrid biomolecular diodes that operate on the same principles as photosynthesis. In photosynthesis, plant cells use two specialized photosystems—photosystem I (PSI) and photosystem II (PSII)—that reside in separate spaces. When light is absorbed, the light energy is converted into an electric voltage across the space between the two systems. The systems are clearly identifiable—about 6 nanometers in size—and can be extracted and incorporated into an electronic device.

The potential for an electronic device using the PSI and PSII systems is considerable. PSI and PSII operate at a minimum of 70 percent efficiency and have been selected by evolution for maximal absorption of sunlight. Thus, they could be incorporated into a device that would be an extremely efficient photovoltaic converter. (Cost-effective silicon photovoltaics currently operate at less than 15 percent efficiency.) The NRC committee envisions a protein-based photovoltaic coating on a Kevlar soldier helmet that is capable of producing enough power to run a laptop computer. The energy could be used directly or stored in batteries, helping to lighten a soldier's load and/or extend a mission's range.

New Materials

There is considerable potential for military applications of biotechnological advances in the field of materials science. Some distinctions need to be made, however, before discussing specifics. Materials for in vivo use (materials that actually will be incorporated into a living organism, such as in wound healing) are called biomaterials. Biomaterials include polymers that could interact with human tissues and help in the regeneration of damaged tissue. Such materials would also be capable of degrading or being absorbed, without any adverse consequences to a patient. Biomaterials must meet certain safety and efficacy standards as prescribed by the Food and Drug Administration (FDA).

Bioinspired materials, on the other hand, are typically intended for external use, such as clothing, camouflage, or armor. These materials do not need to meet any FDA specifications and, indeed, may not even use any biological materials per se. However, their design and manufacture is inspired by biology. Velcro is an excellent example of a bioinspired material, where the fasteners are based on the hooks found on burrs.

Hybrid materials are engineered materials that have at least one component that is a biological molecule. Hybrids may be functional—for example, the bacteriorhodopsin devices already described—or structural—such as engineered bone or enamel. Obviously, structural materials intended for use in the human body will have to meet FDA standards.

Wound healing is certainly an area of military interest. Healing can take the form of repair, where scar tissue forms and may or may not provide for complete return of normal function. Or healing can be regenerative, where the new tissue is fully functional. The biology of wound healing is complex, involving several growth factors—both stimulatory and inhibitory—with their control and interaction at the cellular level still not fully understood.

Current biomaterials used on wounds certainly contribute to the healing process, acting as carriers for growth factors, antibiotics, and procoagulants. Mostly, however, the current materials serve as little more than coverings that are eventually removed, allowing the body to heal itself. The future of wound-healing biomaterials, though, is richer than that and includes coverings that replicate the cellular microenvironment. That is, the biomaterial covering will provide all of the growth factors necessary to stimulate new blood supply, regenerate desired cell types—rather than forming scar tissue—and stimulate cell growth. Since the coverings would not use synthetic materials, a patient would resorb them easily as he healed.

Similarly, biomaterials can be developed to control excessive bleeding. Currently, excessive bleeding accounts for 55 percent of battlefield deaths. Fibrin, a protein found in blood, and certain adhesive proteins found in barnacles could be fashioned into biosealants to slow or stop bleeding. Self-replicating biomaterials would aid in wound healing, and artificial skin would be especially helpful for burn victims. Bone regeneration technology is already at an advanced stage, and the directed growth of bone eventually will become routine. Forward deployed biomanufacturing facilities could produce specific biomaterials on demand, greatly improving patient care.

As intriguing as the medical possibilities are, the potential for new materials goes beyond the medical use of biomaterials. Bioinspired and hybrid materials have several possible military implications. Copying the microscopic organizational structure of a wide range of biological organisms—for example, nacre of abalone (mother of pearl)—may lead to materials that, like the shell, are impact resistant. In fact, it has been demonstrated that replicating such hierarchical structures at the nanometer scale results in materials with unexpected and improved properties. Using mother of pearl as a model, a Pennsylvania firm currently manufactures tiles for use in military aircraft armor panels.

Altering the natural building blocks of existing biomaterials may also yield improvements. For example, bacteria can produce silk, although the process presently is not cost-competitive with silk worms. However, with genetic engineering of silk proteins, improved versions might be developed that could have military applications and make silk economical for bacterial production.

Biology can also provide the materials and inspiration for advances in military clothing and concealment. The color patterns exhibited by bird feathers and some fruits are the result of structural patterns that diffract light. Such mechanical effects could be easily incorporated into camouflaged equipment and clothing. Similarly, chameleon-like behavior—where clothing and equipment change to match the environmental background—is an excellent bioinspired application with military value.

Bacteriorhodopsin has a strong affinity for microwave absorption (especially in the 3–40 gigahertz range) and could be the basis for microwave-absorbing paints. Plant proteins could also be the basis for paints that would have the same infrared reflectivity as trees or grass; equipment painted with such materials would be undetectable by enemy infrared detectors.

Biosensors

Biosensors are broadly defined as devices that query the environment for specific molecules or life forms. The targets can be dispersed as aerosols, suspended in liquids, or present as solids. Sensing systems are actually composed of several component steps, and any one sensor may perform any or all of them: detection, capture, concentration, and derivitization and analysis of samples. Some of those functions are typically done at a laboratory bench. Miniaturized sensor systems that can perform all of the functions, including the lab bench ones, are referred to as a laboratory on a chip.

A network of biosensors could considerably improve a commander's view of the battlefield. Some researchers envision soldiers wearing wristwatch-style biosensors that are sensitive to a variety of target molecules. In effect, each soldier would become a detection device and warn of a possible biological or chemical attack. Also, such sensors could be used to monitor the health and well being of entire units. For example, early signs of infection could be detected in time to treat soldiers before they became seriously ill. Or sleep deprivation could be monitored and units given time to rest before being committed to further action.

Shortening the Logistics Tail

Reducing the military's tooth-to-tail ratio is a constant pursuit. A 1999 NRC report recommended that the Army acquire technologies to reduce both weight and volume of systems and materials.¹⁷ Biology can make significant contributions to that effort.

Miniaturizing devices—thus reducing both weight and volume—is the goal of micro-electro-mechanical systems (MEMS). Incorporation of biological components into MEMS is well illustrated by the laboratory on a chip example. With MEMS devices, tasks that require a complex sequence of laboratory operations can be performed on a device about the size of a sugar cube. Not only is there a savings in size and weight, but there is also a reduction in the amount of chemical reagents needed, as well as less demand for manpower. The 2001 NRC report envisions leveraging multiple lab-on-a-chip technologies and incorporating sensors, laboratory tests, and antidote delivery systems into a biochip to protect troops from chemical and biological agents.

Functional foods are another promising area where biotechnology could help shorten military logistics demands. These foods provide something more than normal nutrition; they can contain so-called nutraceuticals that provide compounds offering both nutritional benefit and health protection. For example, foods could be bioengineered with naturally occurring antimicrobials that inhibit certain pathogens known to exist in a given operational area. Or foods could be designed with vaccines in them, and an army could be vaccinated quickly and efficiently by distributing genetically engineered food.

Producing and supplying foods that maximize digestion could be another way to shorten the logistics tail. With more complete digestion, less food would provide the same amount of energy. Foods could be designed with less need for refrigeration and thus reduce the need for such equipment. Biological tagging could also be accomplished with engineered foods. By requiring everyone in allied units to eat selected foods containing certain proteins or organisms, ready identification of someone as friend or foe when interrogated by sensors would be possible.

With the increase in operations that require smaller and more mobile forces, there is a need for less cumbersome energy sources. Presently, fossil fuels and batteries—all of which must pass through logistical channels starting in the United States and ending on some distant battlefield—meet most military energy demands. Although still in the early stages of development, biological photovoltaics eventually might go a long way toward meeting the demands of faster-paced operations.

Biological photovoltaics would be based on the PSI and PSII systems of photosynthesis, with the flow of electrons being initiated by the absorption of sunlight. The efficiency of such a power source could be enhanced through genetic engineering. There are many technical hurdles to solve before biological photovoltaics become a reality, but the logistical implications of having a solar-driven energy source are evident.

Currently, biofuels offer a renewable source of liquid fuels for vehicles. Ethanol production technology is well developed, with many areas in the United States blending it into gasoline as a seasonal additive to help control air pollution. The future of ethanol production, however, will be in manufacturing the fuel from biomass

(the leaves and stalks of agricultural crops) as opposed to the present method of converting grain. (Even advocates of a future hydrogen-based economy agree that biomass could be the source of hydrogen for fuel cells.) Ultimately, one can foresee transportable conversion facilities that use locally available biomass and waste products, generated by the military itself, to manufacture ethanol, thereby significantly reducing the logistics tail for both liquid fuel and waste disposal.

Warfighter and Health Performance

Knowing a soldier's genetic profile could be useful for many reasons. Having such information could assist in selecting individuals for certain missions. Is a particular soldier well suited for high altitudes based on genetic factors related to his blood oxygen carrying capacity? If injured, does his genetic profile suggest that one therapeutic approach would be preferable to another? If an enhancement factor were available—for example, a drug that gives temporary relief from sleep deprivation—would this soldier benefit or possibly have an adverse reaction?

Delivering therapeutic agents—drugs and/or proteins—is one logical consequence of using genomic data and is an area filled with new approaches. Rather than injecting a soldier with a desired compound, implanting devices capable of controlled release may be a preferred option and is well within our current technological ability. Implantable devices that are self-activating—based on sensors that provide feedback information—will be the next step. Also, as suggested above, implantable devices could be used to deliver antidotes automatically if a sensor detects a soldier's exposure to toxic agents.

Implantable devices, of course, hold potential difficulties as well as possibilities. There may be incompatibility between the devices and a human body, triggering any number of immune reactions. Even the presence of scar tissue at the site of insertion can affect the delivery and/or uptake of any compounds released by a device. The 2001 NRC report projects that within 25 years, implantable devices could be replaced by so-called somatic gene therapy. In this approach, DNA-coated pellets would be fired into a patch of skin. The DNA would enter the skin cells that were fired upon and begin to manufacture desired proteins. As the altered skin cells die and slough off, the proteins would no longer be produced, and their therapeutic/enhancement effect would cease.

Building electronic devices that are compatible with the nervous system has been an active area of research for years. The ability to restore damaged nerves is an obvious goal with implications for any number of neural disorders. Just as likely, and potentially as useful, would be the ability to impart enhanced neural functions—especially hearing and vision—with implantable devices.

The Office of Naval Research (ONR) is conducting several medical investigations, including ways to control pain without degrading performance and researching oxygen-carrying blood substitutes. Another ONR project is examining ways of placing injured warfighters in suspended animation, to slow their metabolic rate.¹⁸

Biomimetics and Organismic Behavior

Most of the biology discussed herein is an exploitation or adaptation of processes taking place within a single cell. Many things that animals do as individual organisms, or as groups, also have military utility.¹⁹ For example, the ability of an insect to move across rugged terrain is vastly superior to that of a soldier traveling on foot or even riding in a vehicle with wheels or tracks. Robot vehicles that can move across uneven terrain, using six legs, would have considerable use. Scientists at the Office of Naval Research have built the prototype of a robo-lobster as well as a robo-scorpion. These are all examples of bioinspired engineering projects that do not necessarily make use of biological materials.

Swarming behavior is another example of a biological phenomenon well worth mimicking. Unmanned aerial vehicles (UAVs) flying in swarms could follow a predetermined route into a denied area. If the route were compromised, the swarm could find an alternate route. Even if some UAVs were lost, the majority of the swarm could complete the mission. To mimic such behaviors will require a greater understanding of the underlying neurology of swarming insects, as well as significant computing power to model it.

Brave New World, or New World Bravery?

Some view the pursuit of a bioengineered future as a greater nightmare than even Aldous Huxley could have imagined. Others

This Is the Future

(A fictional scenario adapted from *Exploring Biotechnology: Opportunities for the Department of Defense, Critical Review and Technology Assessment Report, 2002*.²⁶)

September 2020, Washington, DC

For the past decade, the United States has been committed to researching the potential military applications of biotechnology. With the support of preceding Secretaries of Defense, the Department of Defense (DOD) has experienced a robust infusion of biotechnology related capabilities into the areas of materials science, human performance, military medicine, and organizational processes. The current Secretary of Defense is continuing advocacy of new biotechnology uses and overseeing their realization into joint and service core capabilities.

Human intelligence reporting suggests al Qaeda terrorists have recently reestablished themselves in the mountains of northern Afghanistan. They are attempting to build an underground state-of-the-art biological weapons (BW) facility, relying upon the expertise of scientists previously associated with the now-defunct Iraqi BW program. The President has authorized a preemptive strike to destroy the underground facilities. Specific location data are required prior to launching an attack with precision munitions.

Fort Bragg, North Carolina

Joint Targeting Team Alpha of the U.S. Stealth Joint Task Force is notified that they will deploy to Southwest Asia within 36 hours. The team will insert 65 miles behind enemy forces, in the Badakhshan Province of northern Afghanistan, to deploy a swarm of unmanned aerial vehicles (UAVs) fitted with sensors to detect the presence of common laboratory chemicals used in the growth of biological agents. Team Alpha is a special unit assembled specifically for operations in Southwest Asia. The team consists of six warfighters from the Army, Air Force, Navy, and Marines. All individuals were chosen for the team because of their favorable genetic disposition to high altitude/mountainous operations. They have been taking food supplements with bioengineered ingredients to enhance their genetic predisposition to tough mountain operations and harsh environmental conditions. Their elevated red-blood cell count and cellular resistance to cold weather will

be needed in the rough, mountainous terrain. The next 36 hours will be spent preparing Team Alpha for its mission.

Upon notification of Team Alpha deployment, the Army Center for Geographical Diagnostics at Fort Bragg conducts an evaluation to determine the endemic diseases in the Badakhshan region. After evaluation, the Center prepares a customized immunization regimen to boost team member immune systems before the mission. The team first receives the standard Southwest Asia immunizations (malaria, hepatitis, and dengue fever), which are administered to the team during lunch, contained in genetically altered alfalfa. Their immune systems are then boosted with an injection of a genetic vaccine created specifically for diseases unique to Badakhshan Province and the Afghan threat portfolio (hemorrhagic fever and anthrax II).

After lunch, Team Alpha moves to the accelerated learning module (ALM) to receive mission briefings. Here, the team is given cognitive enhancing drugs, originally developed for the treatment of Alzheimer's disease. This enables Alpha to receive and comprehend in-depth situational and intelligence briefings in a short period of time. In several hours, the team is able to learn material that under normal circumstances would take several days.

C+1

After completion of their ALM briefings, Alpha moves to the bio-equipment depot. Each soldier is outfitted with an advanced, biotechnologically engineered flak jacket. In addition to providing biomaterial-armored protection, the flak jacket allows the vital signs and overall medical condition of the soldiers to be monitored throughout the mission. The jacket is also capable of monitoring for the presence of chemical and biological warfare agents. In the event the soldier is exposed to chemical or biological attack, the jacket will indicate its presence and administer the available antidote. The jacket also contains micro heating and cooling units that work intermittently, depending on the difference between the body and external temperatures.

At the depot, the team is issued their BIO-ROVER. The BIO-ROVER is a bioengineered drone that can fully support a deployed team. It is a self-propelled, six-legged device that can maneuver across rugged terrain at velocities equal to human running speed. The drone can be transported into the field in the

view it as simply the next courageous step in humanity's march into the future. Princeton biologist Lee Silver warned in his 1997 book, *Remaking Eden*, of a two-class system with rich, genetically enhanced "GenRich" types lording it over poorer, inferior "Naturals."²⁰ Others, however, note that there is no such thing as a "superior" or "inferior" genome. "Humankind," according to the United Nations guidelines on ethical issues in medical genetics, "depends for its richness and its survival on the interaction of its complex genetic diversity with the environment."²¹

The ethics and morality of war in general, and even of specific weapons systems, have been the genesis of heated debate probably since the first act of human combat. But no historical precedent

exists for debate about the morality of improved/bioengineered body armor or the ethics of enhanced soldier performance. The bioengineered future of the battlefield steps squarely into the middle of the ongoing debate about genetic engineering and presents policymakers with an unprecedented challenge.

Leon Kass, chairman of the President's Council on Bioethics, sums up that challenge: "[I]n the realm of bioethics, the evils we face (if indeed they are evils) are intertwined with the goods we so keenly seek. . . . Distinguishing good and bad thus intermixed is often extremely difficult."²² The final arbiter of good and evil, moral and immoral, ethical and unethical tends to be the legal profession, and policymakers must look there for guidance.

rucksacks of two soldiers and then reassembled. The BIO-ROVER carries medical supplies, a fuel cell energy pack, and a super microcomputer. The computer contains a Bentiom II DNA chip with N4 computational power and protein-based storage capacity. The computer allows Team Alpha access to 16 networks, 100 gigabytes of bandwidth, and all major command and control systems. The drone runs on a fuel cell that can provide power for 60 days. The cell—the size of a car battery—has a hydrogen biomass generator coupled to a hydrogen battery. The BIO-ROVER finds its way by following an electronic tag attached to a team member.

C+2

From nearby Pope Air Force Base, Team Alpha departs for Afghanistan. Due to the high risk of Team Alpha's mission, the Secretary of Defense has authorized nonstop operations during the mission. The team and their supporting pilots will utilize the Long Range Precision Strike sustainment pill, which will inhibit the onset of sleep deprivation for 7 days, allowing the team members to work continuously at a high cognitive level.

Team Alpha is successfully inserted on the ground in northern Afghanistan. The team's immediate task is to assemble the BIO-ROVER. Next, the team begins searching for a good launch site to release the UAV swarms. However, the team discovers that the power supply on the BIO XJ8 transmitter is not working, making it impossible to download the data transmitted by the UAVs. The team contacts the forward manufacturing amphibious vehicle (FMAV) for a resupply. The FMAV is a refitted submarine converted to manufacture and deliver high priority supplies directly to the field. The FMAV is able to manufacture the necessary biofuel cells and load it into a stealth missile, which is launched into the vicinity of the team. The team recovers the missile cargo and replaces the biofuel cell in the transmitter.

C+3

While continuing their mission and launching UAV swarms to "sniff" various cave openings, Team Alpha is unaware that al Qaeda forces have detected the BIO-ROVER. The team is ambushed by enemy forces and escapes with three of its six members injured. The most seriously wounded soldier is critically

injured and hemorrhaging badly. He is administered a genomic-based drug that effectively puts him into stasis, slowing his blood flow and reducing his body's requirement for oxygen. (He will remain in stasis until the team can be extracted and he is reinvigorated at a hospital.) The two other injuries are minor and are treated with the accelerated wound healing applications. Light emitting diode bandages are applied to their wounds, and the soldiers are fully healed within a few hours.

The Air Force begins an extraction operation starting with an airborne deployment of a UAV missile defense and ground attack swarm from a B-2 stealth bomber. The swarm sets up in a 200-kilometer zone over the team to provide cover for the extraction. The swarm is comprised of UAVs with differing capabilities: airborne flak, intelligence surveillance and reconnaissance, communications, and ground attack. The UAV swarm uses a complex adaptive command and control system utilizing algorithms of animal behavior, such as geese flocking, ant path determination, and wolf pack hunter-prey determination. The UAVs react and organize themselves to protect the extraction from a variety of threats. They are successful in suppressing the al Qaeda forces, allowing Team Alpha to be recovered and flown to friendly territory. The UAV swarm is then recalled and returned to an Aegis cruiser in the Gulf of Oman.

C+4

Team Alpha is returned to Fort Bragg and debriefed. It is determined that al Qaeda forces detected the BIO-ROVER with an advanced electro-optical infrared sensor that detected heat from the drone. Their acquisition of the sensors was unknown to U.S. intelligence and was identified as an intelligence gap. The determination triggers the DOD Rapid Acquisition Program (RAP) to reengineer the BIO-ROVER to correct the vulnerability in the system. The RAP program is based on a biological, rather than industrial, metaphor. Using the principle of directed evolution, the original generation set of BIO-ROVERS are cycled through another prototyping and selection process. The most promising offspring are identified to form the basis of a new generation, with one candidate selected for immediate production. The RAP program allows the new BIO-ROVER to be operational within 2 months.

Jeffrey Kahn, a University of Minnesota bioethicist, states that politics and the law always tend to react to science, not guide it.²³ If policymakers are to make timely decisions concerning biotechnology, though, they cannot wait to react to the science.

Biotechnology issues are especially complicated legally and can involve aspects from bioethics, privacy and consent, FDA regulations, intellectual property and anti-trust laws, environmental guidelines, and Federal acquisition regulations. In its 2002 review of biotechnology's future for the military, the Pentagon Office of Net Assessment made the following observations/recommendations:²⁴

- develop clear, unambiguous guidelines for biotechnology legal issues (current laws do not prohibit biotechnology applications presently under consideration, but there is little or no policy or guidance specific to these technologies)

- establish a DOD Institutional Review Board to provide oversight on these issues (modeled on the National Institutes of Health/Department of Energy effort for the Human Genome Project)

- streamline the FDA approval process and allow for approval based on military necessity, significantly reducing the current 8-year average

- revise existing Federal antitrust laws to facilitate cooperation between DOD and industry to allow for quicker product development

- revise existing Federal and DOD regulations to allow for increased speed and flexibility in bringing promising technologies to the battlefield.

To effect such broad change—change that will be necessary for DOD to exploit the value of these rapidly developing technologies—will take more than the establishment of one or two interagency working groups within the Federal Government. The Office of Net Assessment report further calls for the establishment of a new organization within DOD—possibly the Office of Biotechnology and Life Sciences. The new organization would be responsible for identifying relevant technologies and research; facilitating coordination among industry, DOD, and academic entities; and overseeing the previously cited legal and ethical issues.

A major goal for such a new entity will be the clear separation of biotechnology for medical/defensive means and the use of biotechnology for the smaller/lighter/faster/enhanced warfighting capability desired for the future: the historic view of biology and the battlefield versus the new vision. Budgetary reality is the most obvious place to manifest that division. In fiscal year 2000—the last year for which data were available—DOD expenditures in biotechnology were only \$580 million, representing just 3.2 percent of total Federal spending in biotechnology. However, roughly half of the DOD expenditure (\$296 million) was for medical/defensive measures.²⁵ If DOD is to capitalize on the modern uses of biology, greater sums of money must be directed to addressing warfighting issues.

Biotechnology is progressing at a dizzying rate. What seemed like science fiction just a few years ago is now commonplace. Bureaucratic bravery—often one of the most demanding acts of courage—is presently needed to bring about the necessary institutional changes to move DOD into the new world of biology and bring its full potential to the battlefield.

Notes

¹ "History of Biological Warfare," accessed at <<http://www.gulfwarvets.com/biowar.htm>>.

² "History of Biowarfare," accessed at <http://www.pbs.org/wgbh/nova/bioterror/hist_nf.html>.

³ Rob Stein, "Science Notebook, BIOLOGY: Anthrax as a World War I Weapon," *The Washington Post*, June 29, 1998, A2.

⁴ Ibid.

⁵ Ibid.

⁶ Ibid.

⁷ Ibid.

⁸ "Highlights in Army Medical Department History," accessed at <<http://www.armymedicine.mil/armymed/about/history/highlights.htm>>.

⁹ Ibid.

¹⁰ Ibid.

¹¹ Carol Ezzell, "Proteins Rule," *Scientific American* 286, no. 4 (April 2002), 40–47.

¹² "Protein," accessed at <<http://encarta.msn.com/encnet/refpages/RefArticle.aspx?refid=761565946&pn=1#s1>>.

¹³ Any given protein does not necessarily use all 20 of the amino acids, and it can have multiple copies of the ones it does use. Thus, they can be quite large. Theoretically, two proteins could use the same amino acids but be different in function because the amino acid sequence was not the same.

¹⁴ "Protein."

¹⁵ "Recombinant DNA Technology in the Synthesis of Human Insulin," accessed at <<http://members.ozemail.com.au/~ilanit/dna/html>>.

¹⁶ Board on Army Science and Technology, National Research Council, *Opportunities in Biotechnology for Future Army Applications* (Washington, DC: National Academy Press, 2001), 15.

¹⁷ Board on Army Science and Technology, National Research Council, *Reducing the Logistics Burden for the Army after Next: Doing More with Less* (Washington, DC: National Academy Press, 1999).

¹⁸ "A Future Naval Capability: Warfighter Protection," accessed at <<http://www.onr.navy.mil>>.

¹⁹ Alan Rudolph, seminar remarks at the 23rd Army Science Conference, December 2002.

²⁰ Lee Silver, *Remaking Eden: Cloning and Beyond in a Brave New World* (New York: Avon Books, 1997), 281–293.

²¹ "Proposed International Guidelines on Ethical Issues in Medical Genetics and Genetic Services," accessed at <<http://www.who.int/ncd/hgn/hgnetic.htm>>.

²² "The President's Council on Bioethics," accessed at <<http://www.bioethics.gov>>.

²³ "The Politics of Genes," *The Economist* 359, no. 8217, 22.

²⁴ Jerry B. Warner et al., *Exploring Biotechnology, Opportunities for the Department of Defense, Critical Review and Technology Assessment Report*, January 31, 2002.

²⁵ Ibid.

²⁶ Ibid.

Defense Horizons is published by the Center for Technology and National Security Policy through the Publication Directorate of the Institute for National Strategic Studies, National Defense University. Defense Horizons and other National Defense University publications are available online at <http://www.ndu.edu/inss/press/nduphp.html>.

The opinions, conclusions, and recommendations expressed or implied within are those of the contributors and do not necessarily reflect the views of the Department of Defense or any other department or agency of the Federal Government.

Center for Technology and National Security Policy

Hans Binnendijk
Director