



Biomedical Engineering at APL: Guest Editor's Introduction

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APL, an organization principally postured to contribute to national security, has achieved international recognition for its research and engineering accomplishments in biomedicine. Imaginative researchers have produced scientific studies and experiments that have increased the knowledge and understanding of complex causes of disease and their impact on humans. Laboratory engineers have skillfully developed technology that has opened the way for research in several clinical specialties, as well as made it possible to solve problems confronting health care providers.

This issue the *Technical Digest* primarily describes APL accomplishments in developing biomedical technology for applications important to government and nongovernment sponsors and for those most likely to benefit directly from the engineering initiatives, namely, the astronaut corps, active duty military personnel, health care professionals, and the population at large.

BIOMEDICAL TECHNOLOGY

The APL Science and Technology Council included Biomedical and Biochemical Technology as 1 of 10 categories in a taxonomy describing the current and anticipated climate for technology development at the Laboratory.¹ Following an outline provided by the Biomedical Engineering Society of the Institute of Electrical and Electronics Engineers (IEEE), the Biomedical Technology category alone can be subdivided into 13 elements (a.k.a., the interdisciplinary fields of biomedical engineering). APL staff members have compiled accomplishments in all of these elements in the Laboratory's nearly 40 years of work in biomedical research and technology development.² The technology described in this issue fits comfortably into at least six of those elements. They are

1. Biomechanics: study the static and fluid mechanics associated with physiological systems
2. Biosensors: detect biological events and their conversion to electrical signals
3. Physiological modeling, simulation, and control: use computer simulations to develop an understanding of physiological relationships
4. Biomedical instrumentation: monitor and measure physiological events often requiring development of biosensors

5. Medical informatics: interpret patient-related data and assist in clinical decision making, including expert systems and neural networks
6. Medical imaging: provide graphic displays of anatomical detail and physiological function

The remaining seven elements are medical and biologic analysis, rehabilitation engineering, prosthetic devices and artificial organs, biotechnology, biologic effects of electromagnetic fields, clinical engineering, and biomaterials.

PROBLEMS AND SOLUTIONS

Human Exploration of Deep Space

In January 2004, President George W. Bush outlined a plan for NASA's future exploration of the solar system that included human missions to the Moon and Mars.

Astronauts face numerous and extreme health-related problems and physical and psychological challenges on space missions of 2- to 3-year duration, which would be required for the greater than 118 million mile roundtrip to Mars. NASA sponsors the National Space Biomedical Research Institute (NSBRI), a consortium of organizations, to study and develop countermeasures, or solutions, for biomedical problems anticipated during long missions beyond Earth's orbit. The Johns Hopkins University is a charter member of the NSBRI and is represented by individuals from Johns Hopkins Medicine and APL.

Elements of the deep space environment—weightlessness, reduced gravity, and radiation fields—will affect the performance of human systems such as the musculoskeletal system, cardiovascular system, and blood and immune systems. Humans, accustomed to conditions on Earth, will experience a radically different environment for a prolonged period of time. The reactions of the body and mind, if not mitigated or conditioned, could impact astronaut health and performance, and thus jeopardize the completion of tasks and perhaps an entire mission.

For example, an astronaut's musculoskeletal system (i.e., the bone, cartilage, joints, tendons, ligaments, bursae, and muscles) will react to a weightless environment by losing muscle strength³ and bone mass. Without countermeasures, this loss of bone mass is estimated to be 20% or more during a 2- to 3-year mission.⁴ The level of loss and its corresponding weakening of bone and muscle increase the risk of fractures. In addition, the loss of bone mass increases the likelihood of a co-morbidity or a second disease state forming kidney stones.

A group led by Harry Charles reports on achievements and progress in developing a device to accurately determine the specific location of bone loss and geometric changes in bone structure. The team is developing a technology known as the Advanced Multiple Projection Dual Energy X-ray Absorptiometry (AMPDXA)

scanning system to measure bone loss and structure and to assess the risk of fracture in space. Two prototypes were planned en route to development of an AMPDXA system suitable and qualified for spaceflight. The first prototype was used to verify principles and theoretical predictions. It also demonstrated improvements in spatial and contrast resolution when compared to a commercial DXA scanning system. The second prototype version, which is currently being developed, will be used at NASA's Johnson Space Center for pre- and post-flight measurements of astronauts, contributing data to further studies of the deleterious effects of microgravity environments. In the future, this instrument, or a similar one, could be used for mobile osteoporosis screenings and to identify people susceptible to stress fractures.

In general, another human body system, the cardiovascular system, functions well in space.⁵ However, the reduction in gravitational forces alters or degrades the conditioning (deconditioning) of the cardiovascular system and impairs its ability to re-adapt to gravity. After long missions, astronauts experience a drop in blood pressure, leading to faintness upon standing (orthostatic intolerance) and a reduced capacity for exercise and other physical activity. Not surprisingly, these conditions limit an astronaut's ability to function properly. Furthermore, little is known about the effects of long-term spaceflight on cardiac atrophy (or wasting), or whether spaceflight makes the heart susceptible to life-threatening rhythm disturbances (cardiac arrhythmia).

A team led by James Coolahan reports significant progress in developing a tool for simulating the human body's response to exercise in space. The simulation represents a remarkable step forward in the quest for a better understanding of the effects of exercise in conditioning human explorers for the deep space environment. The team completed a prototype version of a sophisticated simulation of the 25-min cycle ergometer exercise protocols currently used by U.S. astronauts. This was accomplished by integrating simulations of the cardiovascular system, blood flow regulators, whole-body lactate metabolism, and respiration. The simulation was the first successful application in the United States of a new commercial standard—IEEE 1516—for developing and exercising interacting federations of simulations.

Force Health Protection

The phrase "force health protection" denotes the medical portion of the DoD's comprehensive concept for protecting assets. It prescribes steps that should be taken by individuals, commanders, and organizations to promote, improve, conserve, or restore the mental and physical well-being of service members as they encounter an extremely diverse range of military activities and operations. The prescription for a healthy and fit

force includes preventing injuries and illness, protecting against health hazards, and providing medical and rehabilitative care to those who become sick or injured anywhere in the world.

Initial treatment and evacuation of the sick and injured must be planned for austere environments characterized by limited diagnostic and life-support equipment. Moreover, acute and resuscitative care is labor intensive and frequently administered by non-physician personnel to prevent immediate loss of life or limb and to ensure that the patient can tolerate evacuation for the next level of care. Military casualties may wait for hours before receiving definitive health care (i.e., care that normally leads to rehabilitation, return to duty, or discharge from the service).

Emergency treatment is particularly effective if administered during the “golden hour” (the first hour after a soldier is wounded) and the time the soldier is most likely to die.⁶ By providing acute and resuscitative care close to the scene and the instant of wounding, as well as during evacuation, the services greatly improve the injureds’ chance of survival.

The military services value technology that will improve their ability to save lives and treat serious injuries. For example, DARPA is investigating concepts for the next generation of portable, automatic ventilator devices. There is need for ventilators that can manage oxygen flow without cumbersome oxygen tanks and without requiring the presence of trained medical personnel at the side of the injured.⁷ The article by Charles Kerechanin et al. reports on the successful development of a lightweight, easy-to-use, portable ventilator with physiological sensors and medical diagnostic capability for use by the Army in delivering battlefield care to the injured. The device operates without oxygen tanks. The article also describes how the engineering team then used their knowledge and understanding of the problem and technology to creatively develop a second ventilator suited for situations in which emergency response personnel must provide ventilation support to mass casualties.

The Medical Officer of the Marine Corps once was asked what he saw for Marine Corps health services in the future. He answered that the Corps needs to develop better first responder and casualty evacuation capabilities, and just as importantly, the Corps needs to ensure fit and resilient Marines and sailors.⁸ During training and deployment, they are at risk for injury, incapacitation, and degraded performance resulting from inhaled toxic gases, blunt trauma, blasts, directed energy, vehicle jolt, and stress fracture.

Problems involving the musculoskeletal system are the most common reason for losing Marines.⁸ Liming Voo and his team are investigating ways of identifying people susceptible to stress fracture. They have reached a major milestone in demonstrating the utility of

computational modeling and simulation in the biomechanical assessment of bone stress fracture risks. Future work is expected to lead to quantitative estimates of the likelihood of a stress fracture and greater knowledge of individual bone and muscle conditions, which ultimately could be used while establishing guidelines for optimal training regimens.

Surgery

More than 25 million surgical procedures are performed in U.S. hospitals each year. An even greater number are performed in outpatient clinics and physicians’ offices. When selecting a surgeon, a patient is actually choosing a skilled surgical team. One of the most vital members of the team is the anesthesiologist, who must administer the medication that keeps the patient from feeling pain and sensation, make decisions to regulate critical life functions (e.g., heart rate, blood pressure, respiration) during surgery, diagnose and treat medical problems that may arise during surgery, and finally, restore consciousness at the conclusion of the procedure.

There are three broad categories of anesthesia: general, regional, and local. Most major surgeries—particularly those involving the abdomen, chest, and brain—require general anesthesia. Regional anesthesia may be used for selected major operations to the lower half of the body (e.g., cesarean sections, hip and knee surgeries, and hernia repair). Regional or local anesthesia is common for minor surgical procedures, particularly those involving extremities.

Local anesthesia eliminates pain in a region or segment of the body by blocking signals transmitted to the brain from the site of the pain via groups of nerves in the spinal cord. The article by Wayne Sternberger and Robert Greenberg describes an investigation leading to an ability to measure the effectiveness of anesthesia in blocking the transmissions. The authors present the systems engineering methodology used during development and test of a prototype neural blockade monitor that enables an anesthesiologist to accurately determine the area of the body affected by anesthesia and how numb it is. Tests conducted during surgeries (in this study, radical retropubic prostatectomies) using an epidural anesthetic demonstrated the utility and feasibility for real-time monitoring of the level and density of neural blockades.

The team led by Mehrand Armand reports on the development of a guidance system, a critical component of a computer-aided surgery system, to assist surgical teams in planning and performing minimally invasive surgeries. Minimally invasive surgeries (those that require small incisions) result in fewer complications and less damage to normal tissue, and therefore speedier and less painful recovery by the patient. The article describes a concept for using images for guidance, navigation, and

orientation for hip surgery. Also discussed are accomplishments and plans for future tests to demonstrate and validate the guidance system using cadavers and then a set of 10 patients. This work on computer-aided surgery is supported by the first grant ever received by an APL staff member from the National Institute of Biomedical Imaging and Bioengineering of the National Institutes of Health.

Health Assessment

Rapid advances in computing and communications technologies, which are important to many APL programs, also have utility in the delivery of health care. For example, they enable practical implementation of concepts for offering services to patients in their homes rather than in hospitals, clinics, and physicians' offices. The advancing age and increased mobility of the population, rising costs of health care, and increases in the number of patients discharged from hospitals after shorter stays drive the development of technology for home health services, or, more broadly, outpatient care. Outpatient care is a fast-growing component of today's health care system and an area suitable for telemedicine systems. A telemedicine system typically uses modern technology to enable communication and the transfer of appropriate information between a health care provider at one location and a patient at a different location.

The article by James Palmer and Jeffrey Spaeder describes a telemedicine system called TeleWatch that offers the equivalent of a high-tech house call. It features a capability to monitor patients afflicted with congestive heart failure or diabetes in their home or any location equipped with a touch-tone telephone, and simple devices such as a blood pressure cuff, glucometer, or scale. TeleWatch accepts calls and data from patients to help nurses and physicians spot trouble signs before clinically detectable symptoms appear, thereby enabling health care professionals to treat patients before the condition worsens.

Advances in technologies that enable novel and capable biomedical instrumentation, like advances in computing and communications technologies, have potential for reducing costs while increasing the quality and accessibility of health care. The main technological elements that are likely to influence biomedical instruments include electronics, electromechanical systems, telecommunications, optics, sensors, signal and image processing, and algorithm and software development. Joseph Abita and Wolfger Schneider report on a breakthrough that leads to high-speed, high-fidelity communications through the skin. When coupled with active medical implants such as cardiac pacemakers, defibrillators, or nerve stimulators, this capability shows promise for care providers who wish to monitor and manage medical conditions from a distance without disturbing a patient's normal daily routines.

In an application focused on research more than providing immediate care, Kevin Baldwin et al. describe progress in developing a novel instrument for collecting data with which to analyze the extent of physical, cognitive, and sensory degradations or impairments affecting driving habits. The work will not only enable assessment of the driving performance of the disabled, but may ultimately lead to countermeasures or modifications to driving behavior to accommodate changes in vision and cognition that occur with age.

CONCLUDING THOUGHTS

Collaboration across Laboratory departments and among members of the APL staff and other institutions was critical to the accomplishments reported in this issue. As might be expected, several collaborators are affiliated with departments and divisions of the Johns Hopkins School of Medicine, namely, the Departments of Anesthesia and Critical Care Medicine, Ophthalmology, Orthopedic Surgery, and Radiology as well as the Division of Cardiology. One collaborator is associated with the JHU Department of Computer Science and others are with the University of Washington, the Massachusetts Institute of Technology, Case Western Reserve University, and the PRTON Orthopaedic Hospital in Helsinki, Finland.

Collaborative research and engineering poses many challenges. There are distinct professional languages and organizational cultures within the fields of medicine and engineering that may impede progress while developing technology. Objectives and approaches to technology development tend to differ between physicians and engineers. Physicians may desire simple technological solutions that are compliant with medical protocols, while engineers may seek to develop elaborate new technology that may dictate new protocols and approval for treatment. While developing new technology, physicians may be more accustomed to proving or disproving a single hypothesis about quality of care than conforming to the systems engineering process. That process, along with its seemingly conservative, incremental build-a-little, test-a-little approach, is likely to focus more on technical issues than medical issues, especially during the early stages of development.

The results described by the authors in this issue indicate that impediments to collaboration have been recognized and successfully managed, resulting in technology that is capable of advancing biomedical research and is practical and reliable for clinical applications. Through their collaborations, the principals have played roles in advancing biomedical technology "from the industrialization age to the imaging and informatics age."⁹

There is, in fact, much more worth reporting about the Laboratory's contributions to biomedical research and engineering than is presented here. Future issues

devoted to APL research and development will carry articles on research in neurophysiology and ophthalmology as well as additional applications of biomedical technology. It is my hope that this introduction will spawn an interest in reading each article that follows herein as well as subsequent issues.

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