Biomedical and Biochemical Technology at APL

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Formal biomedical collaborations between APL and the Johns Hopkins Medical Institutions date back to 1965 and have led to a succession of accomplishments in research, clinical devices, and clinical systems engineering. Research efforts in neurology, ophthalmology, radiology, and cardiology are discussed along with selected achievements with biomedical engineering devices that attest to the Laboratory's ability to bring research developments to clinical practice in health care. Another more recent outcome of the persistent biomedical and biochemical work at APL is the application of our skills base to the important area of chemical and biological defense. A few examples of chemical and biological sensor and surveillance efforts are presented that are becoming influential in countermeasures against weapons of mass destruction.

INTRODUCTION

For nearly 40 years, APL staff members have participated in investigations that apply biomedical and biochemical technology to the solution of a broad spectrum of problems. This work has had, and continues to have, a profound impact on the Laboratory's contribution to health care and national security.

For example, since 1965, the formal linkage of APL technologists and scientists to biomedical problems has led to a succession of important collaborations with the Johns Hopkins School of Medicine (SoM) and Hopkins Hospital that continues today.[1,2] This interdivisional activity with SoM and the hospital has resulted in wider collaboration between APL staff and other JHU divisions such as the Schools of Engineering, Nursing, and Public Health. Many products of these efforts such as clinical biomedical devices and diagnostic methods have been catalysts to the process of technology transfer in the form of grants, licenses, and royalties. The federal government's knowledge of and trust in the Laboratory's biomedical and biochemical skills has led to significant APL programs in chemical and biological defense (CBD). These investigations have given APL staff the opportunity to enrich their professional careers by enhancing their education and applying their competencies to biomedical and biochemical problems.

In addition, many technological advances in miniaturization, packaging, telemetry, and materials developed in the biomedical arena have made their way into the mainstream of important APL work for the DoD. The intent of this article is to provide a high-level overview of a few of the investigations that exemplify the Laboratory's significant contributions to biomedical and biochemical technology.

TAXONOMY

It is convenient to choose an overarching taxonomy that comprises biomedical research, biomedical engineering, and CBD. From these, a further breakdown into disciplines or technology areas can follow. For example, the Biomedical Engineering Society of the Institute of Electrical and Electronic Engineers (IEEE) breaks biomedical engineering down into 13 disciplines that range from biomechanics to the effects of electromagnetics on biological systems (Fig. 1). APL staff members have contributed to all these disciplines. The DoD's CBD program uses the taxonomy of contamination avoidance (sensors), individual protection (masks, fabrics), collective protection (area containment, HVAC systems), decontamination (foams, wet aerosols), medical countermeasures (vaccines, casualty management), and modeling (agent fate and transport). Again, APL staff have contributed to all of these taxonomy elements.

BIOMEDICAL RESEARCH AND ENGINEERING

In 1965, following earlier discussions between Frank T. McClure of APL and Richard J. Johns of the SoM, the Collaborative Program in Biomedical Research and Engineering was formed. The program was led by Joe Massey at APL and Dick Johns at SoM. Collaborative work was based on three basic precepts[3]:

1. That technological solutions be sought to address significant biomedical problems
2. That investigators from both SoM and APL be personally committed to solving the problems using their bilateral professional competencies
3. That there be institutional backing from both SoM and APL at the department level to support the endeavor with follow-on objectives to sustain long-standing efforts and to seek follow-on funding

Medical department personnel in SoM arrived at a consensus for their highest-priority challenges and presented their problem definitions to APL staff. The Laboratory, in turn, recruited staff that could apply their expertise. Examples of the collaborative efforts based on these precepts abound and are described below.

Ophthalmology

As a result of the collaborative approach, the Hopkins Wilmer Eye Institute was the first to use an argon laser to photocoagulate blood vessels in the retina to treat diabetic retinopathy. This was a landmark accomplishment for the application of lasers in ophthalmology. Further, these early investigations led to optical engineering improvements in a Zeiss fundus camera that made it possible to view the hitherto inaccessible choroidal vascularization behind the retina (Fig. 2a).

As expertise in eye studies increased,[4,5] APL investigators developed a grant relationship with the National Eye Institute that endured for over 16 years.[6,7] Through variational mathematics and experimentation, APL results dispelled previous theories of light transmission through the cornea and explained how light scattering and corneal structure work together to send images to the retina. This has led to a better understanding of corneal function[8] and, among other things, has provided a framework to assess radiation damage.[9] Figure 2b shows one outcome of an investigation by Russ McCally of

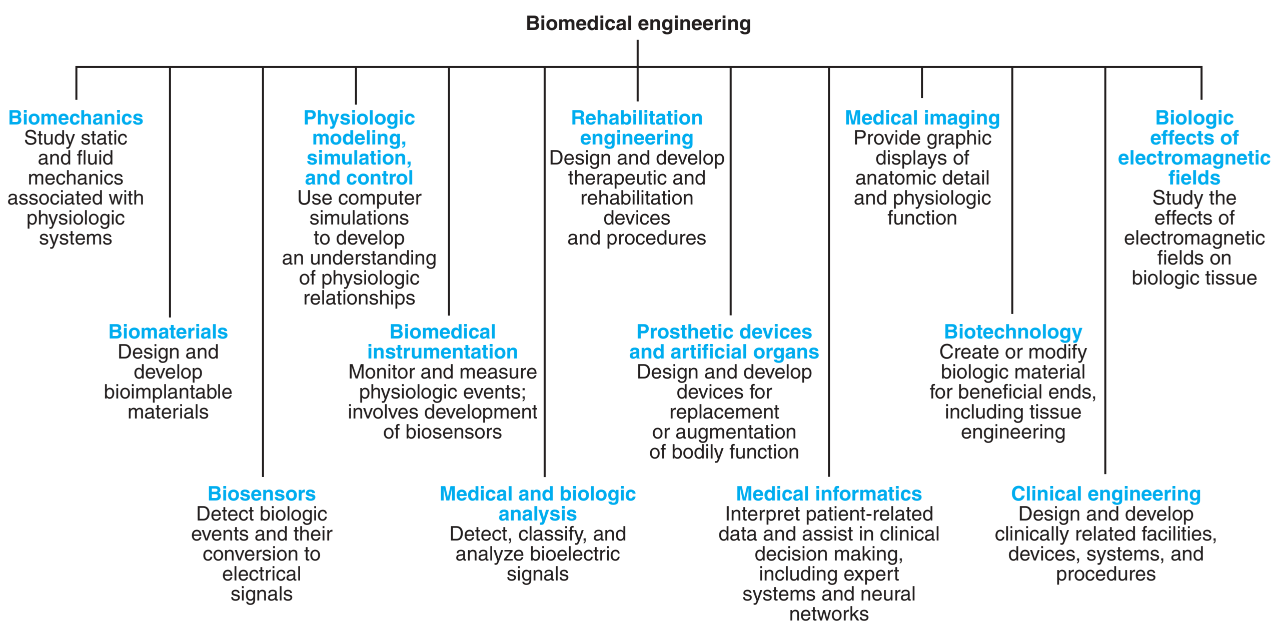

Figure 1. The interdisciplinary fields of biomedical engineering as outlined by the Biomedical Engineering Society of the IEEE.

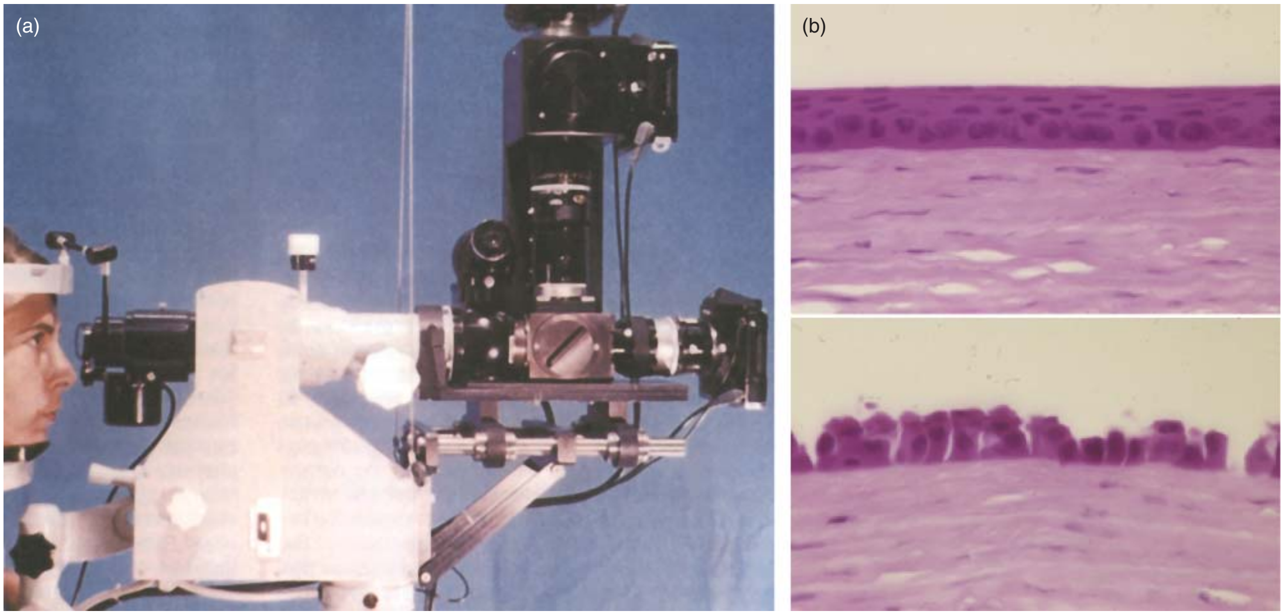

Figure 2. Examples of APL contributions to ophthalmology: (a) the fundus camera using infrared radiation and indocyanine green dye to simultaneously study choroidal and retinal circulation, and (b) results of a study of 2-μm laser radiation damage to the cornea using a slit lamp biomicroscope (top, normal histology; bottom, exposed area histology).

APL that describes laser damage at the 2-μm wavelength. This work, funded by the Army, is tremendously relevant in today's warfighting environment with the increased use of lasers in the battlefield. Since 1997, over 19 refereed publications in ophthalmology have been authored by APL staff addressing topics from laser damage to age-related cataracts.[10]

Neurophysiology

In the area of neurology and neurosurgery, the APL–Johns Hopkins Medical Institutions collaborative program led to a string of accomplishments embodied in the longest-standing neurosensory grant from the National Institutes of Health that endured for 26 years. Several APL collaborations have been undertaken to help understand multiple mechanisms for pain[11] and to aid in the localization and characterization of epileptic events[12,13] and brain edema.[14]

The most persistent collaborative theme deals with the neurophysiological and psychophysical mechanisms of pain.[15,16] Many devices were fabricated and experiments performed to help understand the transmission of neuronal response from the peripheral nervous system to the central nervous system. Figure 3a shows a radiometer-controlled laser stimulator developed at APL that was used extensively in the SoM Department of Neurosurgery for peripheral pain research.[17] It is a good example of the use of APL expertise in optics and electrical and computer systems engineering for medical research.

In addition, microelectronic technology has been used to construct multisite, fine-tipped microprobes for investigating the electrical activity of neurons in living brain issue.[18] Figure 3b shows an example of a six-site probe that was only 1 mm wide. This work has benefited other efforts at APL dealing with the need to properly coat and seal electronics from harsh electrolytic environments.

Figure 3c is a clinical research prototype now being tested to assess small fiber neuropathies and associated neurological diseases. This microprocessor-controlled heat stimulator is used at the bedside to determine thermal pain threshold. APL collaborations in pain research led by Richard Meyer of APL, who holds joint appointments as Professor of Neurosurgery and Professor of Biomedical Engineering at JHU, have led to over 22 publications in refereed journals during the last 5 years.

Oncology

The long-standing APL relationship with the Department of Radiology continues today. In 1975 Dave Grant of the APL Space Department was appointed Director of Radiation Therapy Physics at Hopkins Hospital in an effort to facilitate the applications of systems engineering to a variety of new radiation oncology instruments. The Laboratory helped to integrate complex apparatus into the clinical setting with the assurance that a good physics-based understanding of the radiation treatment resulted in the best use of the equipment. In 1978, Grant was appointed Director of the Division of Clinical Engineering.

Among the many other APL developments of practical value was the Oncology Clinical Information System (OCIS) developed by Bruce Blum. The OCIS is still used today at the Hopkins Hospital. This

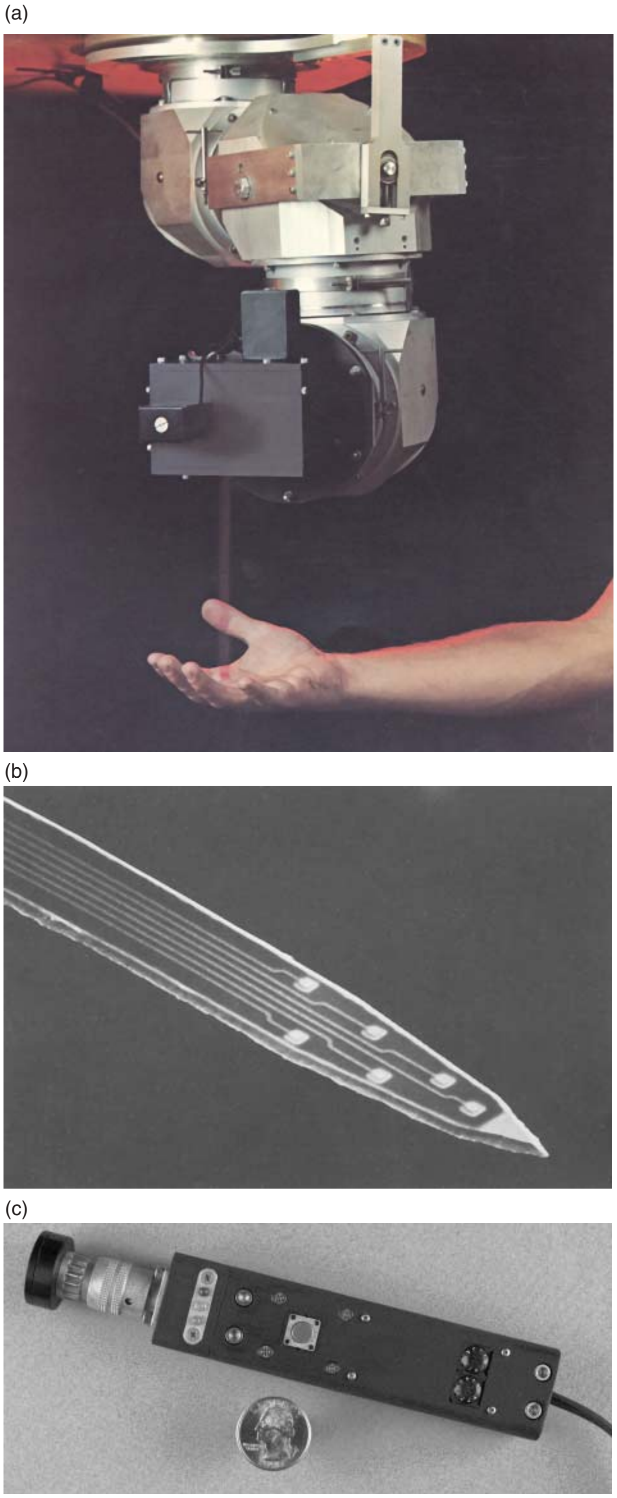

Figure 3. Devices developed for neurophysiological research: (a) APL thermal stimulator using a carbon dioxide infrared laser controlled by a radiometer that remotely senses skin temperature, (b) electron micrograph of a six-site neural probe with 30-μm square electrode pads, and (c) prototype handheld thermal stimulator with skin contact temperature range from 35° to 54°C and interchangeable tip diameters from 3 to 12 mm.

work helped to set the stage for structured database architectures employed by many software engineers. In addition, Laboratory expertise in signal processing and medical imaging has been important for detecting microcalcifications in mammograms[19] and for facilitating faster magnetic resonance imaging of dynamic cardiac functions.[20]

Several APL contributions to medical imaging are reported in the new *Handbook of Medical Imaging* edited by Isaac Bankman of APL.[21] Today, APL expertise in high-speed data networking has resulted in the ability of radiation oncologists at Peninsula Regional Hospital in Salisbury, Maryland, to interact through video teleconferencing with Hopkins radiation oncology experts to plan and execute radiation therapy (Fig. 4). This system not only strengthens the consensus for diagnosis and treatment but also allows the patients in Salisbury access to quicker, local therapy.

Cardiology

Cardiology was one of the initial themes in the original 1965 joint program and has continued to be important ever since. APL research has focused on electrical analogs to cardiac function, fluid dynamic properties of blood flow, and cardiac assist devices. One early APL response to SoM needs was the development of the implantable, rechargeable pacemaker.[22] Using Space Age quality control, packaging, and systems engineering, the Hopkins Rechargeable Pacemaker (Fig. 5a) extended the useful life of implantable pacemakers from 12 months to over 17 years. This development evolved from the early 1960s to the first implant in 1973. Approximately 5900 units were implanted between 1973 and 1984 with an average lifetime of 8 years, limited more by the patient's health than by the pacemaker technology. This effort demonstrated the benefit of rigid prescreening and testing of electronic components for their electronic value and tolerance, as well as the importance of rigorous environmental testing of hermetically sealed packaging, practices that have now been adopted worldwide.

Another Hopkins invention implemented by APL technologists in the late 1980s was the first Automatic Implantable Cardiac Defibrillator (AICD) (Fig. 5b). About the size of a cigarette package, the AICD was programmed to monitor the heart continuously to recognize arrhythmias and to automatically deliver remedial shocks via electrodes on the heart.[23] By the early 1990s, hundreds of AICDs were implanted each month, saving many lives.

Today, several investigations in cardiology continue at APL. For example, Fig. 5c illustrates the application of acoustic instrumentation and advanced signal processing to automatically detect and analyze pediatric murmurs such as those arising from ventricular septal defect.[24] Innocent heart murmurs are commonly detected in clinical practice. The traditional use of stethoscope auscultation can result in expensive testing or referrals to cardiology subspecialists even though

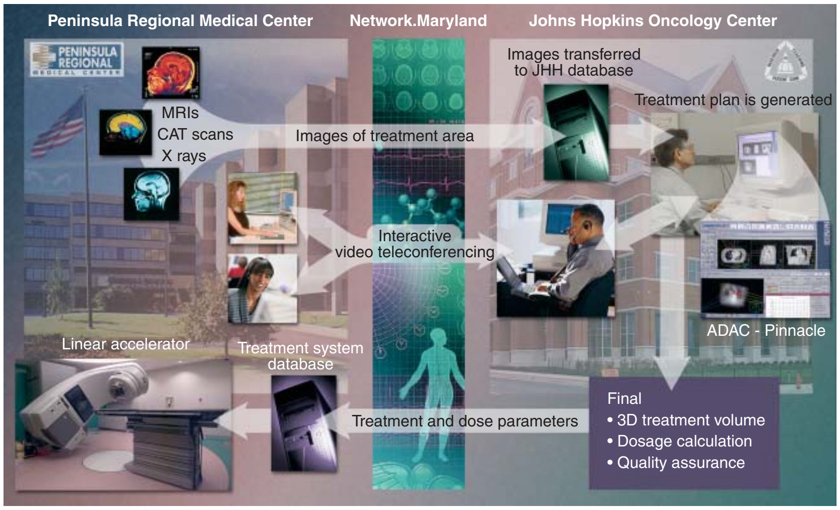

Figure 4. A viewgraph showing features of an APL pilot project. Teleconferencing allows radiation oncologists to plan treatment for patients at the Peninsula Regional Medical Center in Salisbury, Maryland.

few of the patients (10–20%) are eventually found to have pathology. This development will enhance screening at the first point of care and reduce the number of costly referrals.

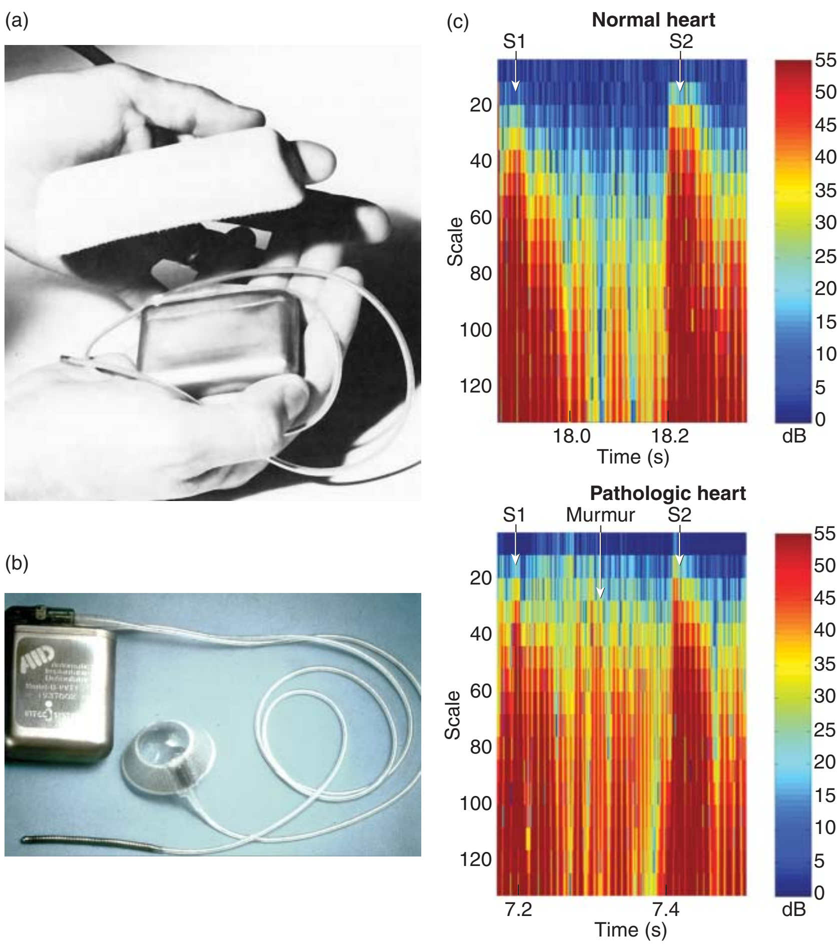

Figure 5. Significant APL contributions to cardiology: (a) rechargeable pacemaker licensed to Pacesetter Systems, Inc., (b) cardiac defribrillator licensed to Ventritex, and (c) signal processing for heart murmur detection and characterization.

Biomedical Devices

In addition to the rechargeable pacemaker and defibrillator, APL has developed many biomedical devices for clinical use and health care. In the early 1970s, several wheelchair chin controllers[25] (Fig. 6a) were designed and fabricated for the Veterans Administration. These mechanical controllers enabled paraplegic patients to attain increased wheelchair mobility and to gain access to facilities without assistance.

In the mid-1980s, APL developed the Ingestible Thermal Monitoring System (ITMS), known as the temperature pill, for NASA to monitor the core body temperature of astronauts (Fig. 6b). This device used an inductive magnetic telemetry interface to help read the pill temperature as it passed through the gastrointestinal tract. It was later commercialized for a variety of other uses.[26] During this same period, the Hopkins nonreusable syringe (Fig. 6c) was also developed to help prevent the spread of AIDS and other communicable diseases attributable to the misuse of syringes. Millions of these devices have been used by the World Health Organization. Both the ITMS and the Auto-Destruct Syringe were first-of-their-kind successes.

The Programmable Implantable Medication Infusion System (PIMS, Fig. 7a) was developed for the NASA Technology Utilization Program to help demonstrate the dual use of space technology.[23] Often described as an implantable "satellite," the PIMS embodies sensors, a computer, and a communications and telemetry system in one package. It provides round-the-clock insulin delivery for the treatment of diabetes for over 500 people. These devices and instruments are excellent examples of the application of basic physics, engineering design and fabrication, systems engineering, and medical review board procedures that result not only in

Figure 6. Biomedical devices developed by APL: (a) low-profile chin controller for a powered wheelchair, (b) ingestible thermal pill licensed to Human Technologies, Inc., and (c) nonreusable syringe licensed to Pharma Plan.

proof of principle but also in technology transfer to commercialization.

In fact, during the last 30 years, APL inventors disclosed over 320 biomedical inventions, leading to over 79 patents and $9 million in revenue via technology licensing to commercial industry. Several new devices are undergoing trials today. For example, Fig. 7b shows the Far Forward Life Support System (FFLSS) developed for the Army to provide automatic, portable ventilation to victims.[27] Many victims will have their breathing sustained by only one technician and multiple FFLSS units. Key to this development is the subsystem integration of many commercial sensors and devices, along with the test and evaluation of electromagnetic interference and vibration.

Biomedical Information Systems

The development and use of information systems has been a very important component of biomedical engineering at APL. In the 1980s, in addition to the Oncology Clinical Information System, Bruce Blum of APL developed the Comprehensive Child Care Program that is still being used by the Hopkins Department of Pediatric Medicine. In 1980 and again in 1991, Paul Hazen and Alexander Kossiakoff, both of APL, conducted the Johns Hopkins National Search for Computing Applications to Assist Persons with Disabilities.[28] Hundreds of entries were submitted. For example, smart keyboards that provided computer access to many handicapped people were developed with custom overlays to permit the use of the computer in nontraditional ways. An audible feedback scheme allowed a blind person using a computer to comprehend and employ a windowed graphical user interface in the same manner as a sighted user. A sound-to-speech translation system using graphical symbols enabled listeners to understand communications from people with mental retardation or severe communications handicaps.

In 1997, Joe Lombardo and Rick Wojcik, both of APL, helped demonstrate the use of mobile computing in a hospital setting that saved administrative time in processing paper records and demonstrated the use of the mobile computer workstation in a clinical setting.[29] The workstation was first demonstrated in the Infectious Disease Nursing Unit at Johns Hopkins Hospital and received an award from the American Association for the Advancement of Medical Instrumentation.

Today two new APL accomplishments are in use at the Johns Hopkins Medical Institutions. Lombardo

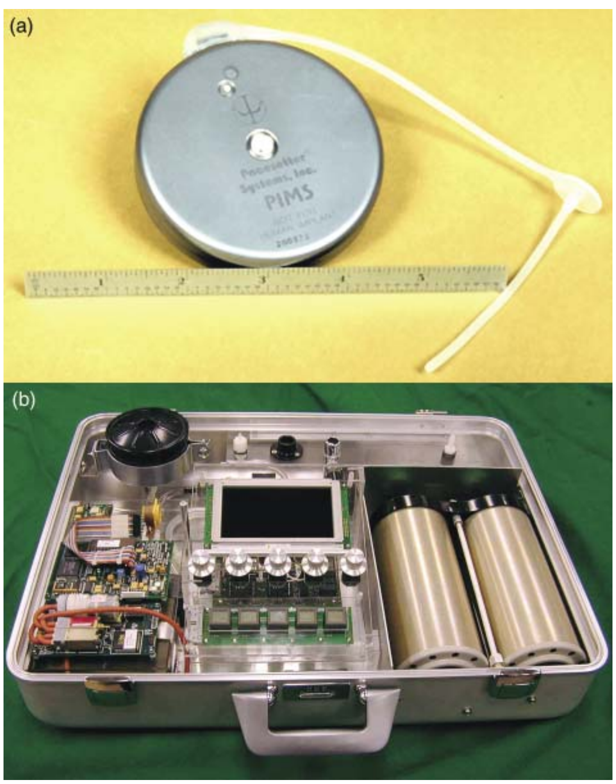

Figure 7. Biomedical instrument systems: (a) Programmable Implantable Medication Infusion System licensed to Mini Med Technologies, Inc., and (b) Far Forward Life Support System.

and Wojcik developed the Faculty Information System (FIS), which helps the Dean of the SoM to track grants, payroll, laboratory space, and clinical income through a series of system modules that collate these data. The FIS provides not only department and division reports but also management-by-exception notifications of schedules, grant deadlines, and research reviews.[30] Wojcik also developed the JHU School of Medicine Admissions Database that processes over 6000 applicants yearly. It tracks the progress of the applicant from initial application submission through matriculation. Both of these systems have received acclaim and might find their way into other medical institutions.

In support of the DoD, APL helped bring telemedicine to practice for the Navy in 1995. The Laboratory's technical expertise enabled surgeons in the USS *Lincoln* battle group to perform the first remote orthoscopic surgery at sea in the Philippines with consultation from medical personnel in San Diego, California, and Bethesda, Maryland. This accomplishment has led to additional naval capability in the form of connective networks across medical centers nationwide. APL investigators have also helped to bring telemedicine to clinical practice at Hopkins Hospital.[31]

Strengths and Challenges

The strengths of biomedical research and engineering at APL are evident as shown in the boxed insert, which lists presentations made to the APL Senior Leadership Team. The 37-year collaboration with the Johns Hopkins Medical Institutions using expertise in ophthalmology, neurology, cardiology, and urology[32,33] has been invaluable in bringing technology to clinical practice. This article cannot adequately describe the entire spectrum of APL activities in biomedicine. Staff expertise in clinical engineering, systems engineering, modeling and simulation,[34] and engineering design[35] and fabrication[36] has helped to sustain a long history of successful biomedical device and medical information systems development.

BIOMEDICAL AND BIOCHEMICAL TECHNOLOGY EFFORTS AT APL

Biomedical Research and Engineering

Evolution of a New Series of Self-Contained Portable Ventilators for Military and Civilian Use
P. N. Cutchis, D. G. Smith, and D. S. Wenstrand

Automatic Blood Sampling System
J. L. Abita, W. Schneider, and R. P. Szczepanowski

Telewatch Patient Monitoring System
J. G. Palmer

Biopsy Device
J. C. Murphy and R. P. Szczepanowski

Corneal Laser Radiation Damage
R. L. McCally and J. A. Bonney-Ray

Advanced Cardiac Systems Integrated and Distributed Modeling
S. P. Murphy, A. B. Feldman, J. E. Coolahan, and R. R. Lutz

Evaluation of Defibrillator High Voltage Capacitors
J. L. Abita, J. Bitman, and E. Nhan

Cortisol Sensor for Soldier Stress and Fatigue Monitoring
D. S. Lawrence

Wavelet Processing of Systolic Murmurs to Assist with Clinical Diagnosis of Heart Disease
C. S. Hayek, W. R. Thompson, C. Tuchinda, R. A. Wojcik, and J. S. Lombardo

Remote Treatment Planning for Radiation Therapy
R. A. Wojcik, J. S. Lombardo, S. A. Loschen, L. Myers, and J. Dicello

Noninvasive Fetal Heart Monitoring from Maternal Surface Electrocardiogram
J. A. Cristion, W. I. Sternberger, E. J. Moses, J. DiPietro, and R. S. Greenberg

Electronic Pain Management System
M. J. Bembenek, W. A. Sellers, and R. S. Greenberg

Assessment of Tooth Health Using Laser-Based Ultrasonics
D. W. Blodgett

Prostate Cancer Detection Using the Bioimpedance Method
D. G. Smith, H. W. Ko, W. R. Drummond, and A. W. Partin

Automated Polygraph Scoring
J. C. Harris and D. E. Olsen

Chemical and Biological Defense

An Array of Time-of-Flight Mass Spectrometers for Rapid Analysis of Aerosolized Chemical and Biological Weapons
T. J. Cornish, W. A. Bryden, S. A. Ecelberger, F. P. Gick, and D. L. Lewis

The Development of MALDI-TOF-MS for the Detection of Aerosolized Bacterial Spores
P. F. Scholl

MALDI Desorption Surfaces and Sample Preparation Techniques
M. D. Antoine, P. F. Scholl, M. A. Carlson, W. R. Drummond, J. R. Stutler, and J. C. Crookston

MASINT (Measurement and Signature Intelligence) Operational Demonstrations
W. I. Sternberger, V. Vigliotti, and S. A. Goemmer

Study of Bioagent Cloud Polarization and Dynamics Using Aerosol Lidar
J. W. Giles, E. W. Rogala, R. M. Sova, and I. N. Bankman

Optical Characteristics of Airborne Bacteria
C. A. Mitchell, M. E. Thomas, S. C. Walts, and D. D. Duncan

Real-Time Decontamination of Spores, Viruses and Bacteria in a HVAC System
R. S. Potember, W. A. Bryden, M. A. Carlson, J. C. Crookston, and J. Jackman

Self-Decontaminating Materials
J. C. Crookston, J. L. Sample, G. E. Southard, and C. A. Kelly

Simulation of Bio-Agent Release in a Room
S. M. Scorpio, R. P. Roger, and A. Brandt

However, APL is one-person deep in critical skill areas such as neurophysics. Furthermore, with the difficulty in sustaining student and postdoctoral participation at APL, and also because of the lack of veterinary facilities and expertise, long-term collaborations are difficult to sustain, which results in erratic funding of a substantial nature. It is clear that the staff at APL wish to continue these collaborative biomedical research and engineering investigations with the Hopkins Medical Institutions. This might be accomplished effectively if we concentrate on fewer focus areas and seek to develop a few centers of excellence that could lead to sustained funding.

We need to enhance APL roles in systems engineering and in technology transfer and to participate in strategic alliances with other laboratories, institutes, and industry. This process would be strengthened by a strategic investment in skilled people and facilities. Our efforts will be fruitful and profound if we keep in mind the basic precepts that formed the backbone of the original 1965 Cooperative Biomedical Program.

CHEMICAL AND BIOLOGICAL DEFENSE

Sensor Development

APL's ability to address chemical and biological problems through the application of basic sciences to sensor systems, as well as our ability to bring a systems engineering discipline to complex processes, has led to a significant involvement in the area of CBD. Several technology areas embody the Laboratory's contributions to CBD. Sampling, sensors, background characterization, systems engineering, agent neutralization and decontamination, aerosolization physics, and computational fluid dynamics modeling and simulation of the fate and transport of chemical and biological agents all contribute to the APL base of investigations.

Initial work in biological sensing for CBD started in the mid-1980s when the APL Space Department and the Technical Services Department collaborated with the Department of Pharmacology and Molecular Sciences of the Hopkins SoM. In this effort, bacteria were profiled using fast atom bombardment mass spectroscopy in support of Army research.[37]

As the result of Desert Storm, APL supported the DoD with the development of a biodetection time-of-flight mass spectrometer (Fig. 8) in the 1995–1996 timeframe.[38] This work continues today with the development of several different versions of time-of-flight mass spectrometer systems intended to detect, characterize, and identify a broad spectrum of bacteria, viruses, and toxins.[39] The potential for a small, fieldable biomass spectrometer that can detect a wide range of threat agents all at once, without the need for bioreagent fluids, is inherent in this APL development.[40]

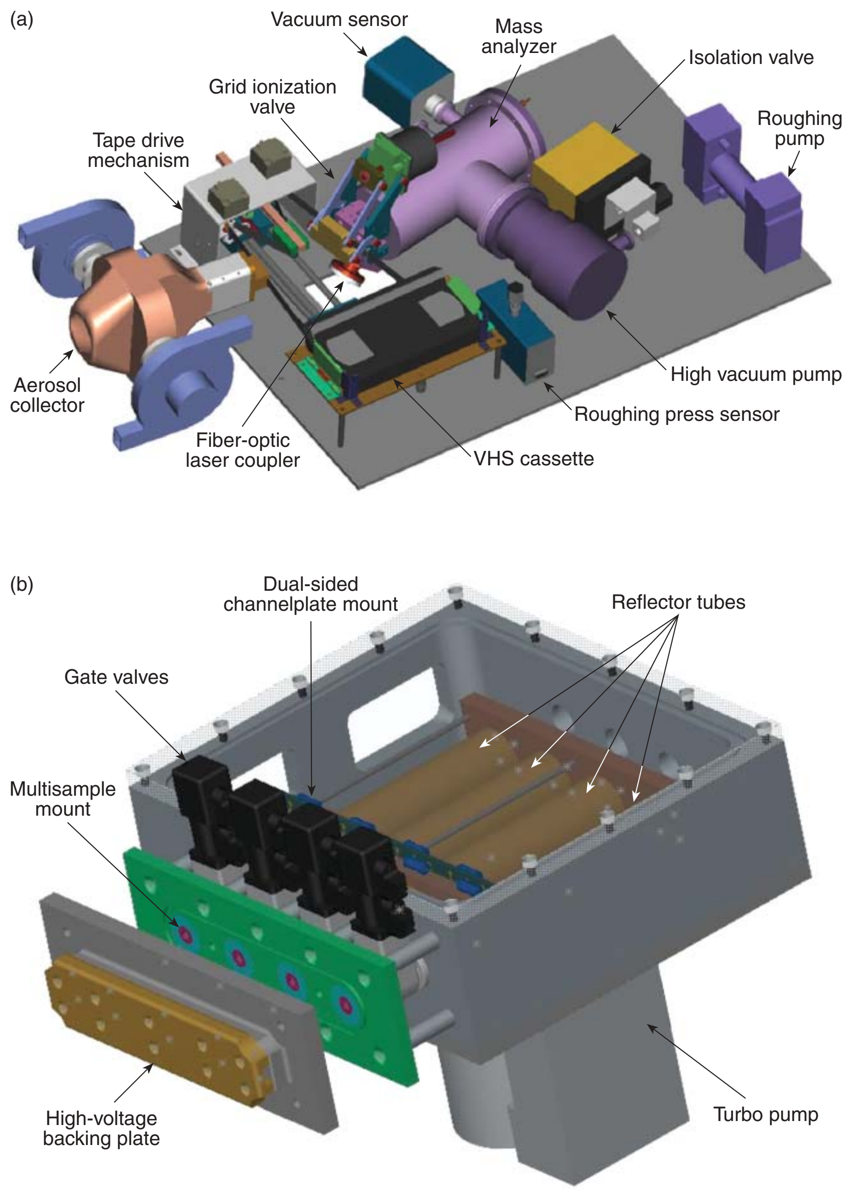

Figure 8. Conceptual drawings for the APL Biological Time-of-Flight (BioToF) mass spectrometer system: (a) fully automated system with single mass analyzer, and (b) quad-array analyzer for prototyping.

Also in the mid-1990s, an affinity chromatography immunoassay sensor for aflatoxin was developed through collaboration with the Hopkins School of Public Health.[41] In addition, molecularly imprinted polymers have been used to develop sensors to detect chemical nerve agent hydrolysis products.[42,43]

Today, many activities are under way to sample the environment and to detect the presence of chemical and biological target substances in the presence of a cluttered background.[44] These sampling technologies range from the high-volume dry collection of biological particulates from the air to the collection of chemical substances in water using solid-phase micro-extraction and membrane inlet technologies. Sensor development continues with the refinement of mass spectral systems (see the boxed insert) and matrix-assisted laser desorption and ionization (MALDI) procedures to optimize sample preparation and identification. Additional work is being conducted using fast gas chromatography for rapid chemical detection and messenger RNA microchip assays for precise biological identification.

Since authoritative detection involves statistical sensor performance in the presence of noise, a large part of the APL effort in CBD addresses the sensor environment. Background environmental characterization is accomplished in two ways. First, environmental samples are physically analyzed in the laboratory by traditional microbial analysis and by chemical gas chromatographic techniques. Second, an information-based biosurveillance system developed by the Laboratory for the state of Maryland uses information from a variety of data sources to detect anomalies in biological behavior. Figure 9 describes the APL biosurveillance system developed for the Network.Maryland Program, which uses information from schools, pharmacies, emergency rooms, and other monitors of health to ensure that any anomalous behavior is presented to and understood by the public health community.

New techniques are also being developed to minimize the viability of biological particulates within HVAC systems by applying engineering methods to exploit the scientific understanding of the destruction of organisms by ozone and ultraviolet light. Furthermore, the movement of biological particulates, as influenced by turbulence and particle size, is being simulated using computational fluid dynamics models and tested using aerosolization facilities at APL. Through these efforts the Laboratory is contributing to the ability to confront biological pathogens in indoor (e.g., building protection) as well as outdoor (e.g., battlespace) settings.

Strengths and Challenges

The Laboratory is well recognized for its strength in chemical and biological sensor expertise, systems engineering, environmental measurements, and test and evaluation experience. In addition, APL laboratory capabilities at various biological safety levels and in several aerosolization facilities are allowing staff to obtain and conduct new investigations. However, because we are understaffed in the biological sciences (e.g., biology, microbiology, plant pathology), the Laboratory's ability to greatly expand research and analysis participation in sampling and sensor programs is limited. Furthermore, APL is understaffed in medical specialties such as epidemiology, symptomatology, and pathology, which are essential to understanding the background anomalies in biosurveillance. Limitations in space and personnel capable of working with licensed chemical agents and biological pathogens also restrict our involvement in these key areas. Therefore, APL is moving toward developing strategic alliances with other laboratories and institutions to expand participation in the compelling CBD area. In addition, the Laboratory seeks to expand our problem-solving participation in the chemical and biological arenas beyond the DoD.

Figure 9. A viewgraph showing the Maryland Bio Surveillance System. Many diverse information sources are used together with APL autonomous algorithms to provide rapid public response to public health anomalies.

SUMMARY

Six Laboratory departments are contributing expertise in the basic sciences of chemistry, physics, microbiology, cell biology, and materials. In addition, collaborations with the Hopkins SoM and School of Public Health are ongoing. Applied mathematics capabilities in signal processing, computational fluid dynamics, modeling and simulation, operations analysis, and imaging are highly sought for the success of these programs. The Laboratory's ability to bring this expertise to practice, both clinically and operationally in the field, relies on our strengths in operational systems engineering, electronics and mechanical design and fabrication, electro-optic design, clinical systems engineering, and telecommunications. All of these talents are used today.

The challenges of the 21st century in health care and national security require that these skills be exploited through the continued dedication of the staff, the staff's resolve to learn new skills, and the outside recognition of the Laboratory's ability to solve important national problems.

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