Partnering with Johns Hopkins Medicine to Revolutionize Health

Sezin A. Palmer, Alan D. Ravitz, and Robert S. Armiger

ABSTRACT

For nearly 60 years the Johns Hopkins University Applied Physics Laboratory (APL) has collaborated with Johns Hopkins Medicine (JHM) to study pressing health and health care problems and develop innovative solutions. Early accomplishments in ophthalmology, neurophysiology, oncology, and cardiology led to better understanding of and new and improved treatments for various conditions. Today, through its National Heath Mission Area, APL is furthering its partnership with JHM to apply rigorous data analysis and systems engineering practices to the diagnosis and treatment of disease. The collaboration leverages the institutions' systems engineering and medical expertise to create a learning health system that will speed the translation of knowledge to practice while enabling new discoveries through the development and application of advanced analytic tools. This article briefly describes how the partnership has revolutionized health and health care and is poised to continue to do so.

INTRODUCTION

At the beginning of this century, the Institute of Medicine published two seminal reports focused on the deterioration of the health care system and the astounding number of deaths due to medical errors in the United States. The first report, *To Err is Human*,[1] highlighted the dire conditions within health care settings that result in preventable medical harms and recommended an approach to build a safer health care system. *Crossing the Quality Chasm*[2] quickly followed with an examination of other problems and limitations across health care and a proposed approach to address the challenges systematically.

In response to these challenges, the National Academy of Engineering and the Institute of Medicine convened a committee of engineers and health care professionals to develop a strategy to leverage engineering tools and technologies to help health systems deliver care that is safe and effective. Their report[3] concluded that the application of engineering strategies and principles that has revolutionized other industries has been neglected in the health care industry.

Recognizing this imperative to bring sound systems engineering principles to health care and medicine and building on a long history of collaboration with Johns Hopkins Medicine (JHM), APL began working to form new partnerships across JHM to explore opportunities to demonstrate the potential value of integrated health systems. These efforts culminated in establishment of the National Health Mission Area at APL in 2016.

In 2020, when faced with the realization that we were in the midst of an unprecedented global pandemic, the decision to establish the new mission area was seemingly prescient. With critical national and international concerns facing both military and civilian populations, APL responded immediately, bringing the full spectrum of APL's technical capabilities to bear on the most significant crisis facing our nation in 100 years.

HISTORY

For over 60 years, successful collaborations between APL and JHM have led to significant and impactful innovations.[4,5] Beginning in 1965 with the Collaborative Program in Biomedical Research and Engineering, engineers and medical doctors across the Johns Hopkins enterprise began working to develop technological solutions to biomedical problems.[6]

Some of the early accomplishments achieved through this program included significant impact in the areas of ophthalmology, neurophysiology, oncology, and cardiology. An early landmark accomplishment of the collaboration was in the use of lasers to treat diabetic retinopathy.[6] Over the course of a 16-year grant from the National Eye Institute,[7,8] APL and JHM established new theories of light transmission through the cornea and explained how light scattering through the corneal structure results in images being formed in the retina.[6,9] In the area of neurology and neurosurgery, APL–JHM collaborations focused on understanding mechanisms for pain.[6,10] APL fabricated devices and supported experiments to understand the transmission of neuronal response from the peripheral nervous system to the central nervous system.[6] Figure 1 shows a radiometer-controlled laser stimulator developed at APL and used extensively in the Hopkins School of Medicine Department of Neurosurgery for peripheral pain research.[11] APL expertise in optics and electrical engineering was a critical enabler for many of the early collaborative successes.[6]

These early collaborations between APL and JHM led to many significant innovations, including the rechargeable pacemaker,[12] which extended the useful life of implantable pacemakers from 12 months to over 17 years,[6] and the first Automatic Implantable Cardiac Defibrillator, which became the new standard, with hundreds being implanted every month and saving many lives.[6] APL's deep expertise in physics and application of systems engineering led to breakthroughs in cardiac devices and radiation oncology.[6]

By the 1990s, APL was engaged in numerous joint biomedical research programs with JHM, supporting the National Institutes of Health and the Department of Defense (DOD). APL was devoting increased internal funding to biomedical programs during this time as well. APL created an Institute for Advanced Science and Technology in Medicine in 1995 and worked on
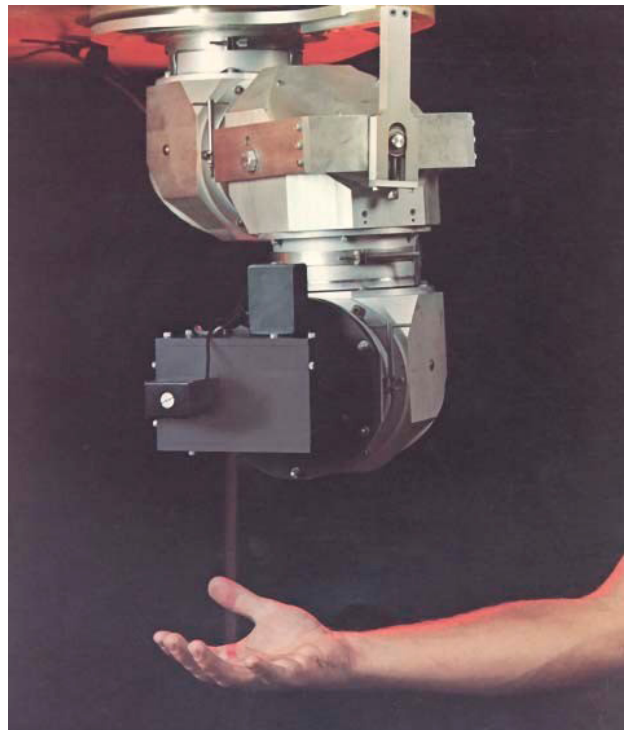

Figure 1. Radiometer-controlled laser stimulator. One of many examples of early APL–JHM collaborations, this device was developed at APL and used to advance peripheral pain research at the Hopkins School of Medicine.

a telemedicine system,[6,13] eye research, a non-reusable syringe,[6] mammogram improvements,[14] an ingestible temperature sensor[6] (tested in space by astronaut John Glenn in 1997), better bone replacement implants,[15] and a fetal heart monitor.[16] Funding from NASA's National Space Biomedical Research Institute over several years led to the development of new technologies to protect humans working in space.[17] The collaborations between APL and JHM over many decades resulted in critical new, lifesaving technologies. These are but a few of the transformative technologies that resulted from decades of collaboration between APL and JHM faculty in the last century.

In 2006, APL established a new Biomedical Business Area with a focus on bringing biomedical technology and capabilities to DOD. The Laboratory's new business unit emphasized the application of scientific knowledge and engineering principles to warfighter health. The strategic thrusts established in the Biomedical Business Area included human integrated systems, biomedical informatics, and applied injury science. Across these areas, key research and development programs focused on applied neuroscience, patient safety, injury biomechanics, and prosthetics. In the area of biomechanics and injury mitigation, new projects focused on developing biofidelic models and characterizing the impact of various forces on the warfighter.[18] These projects
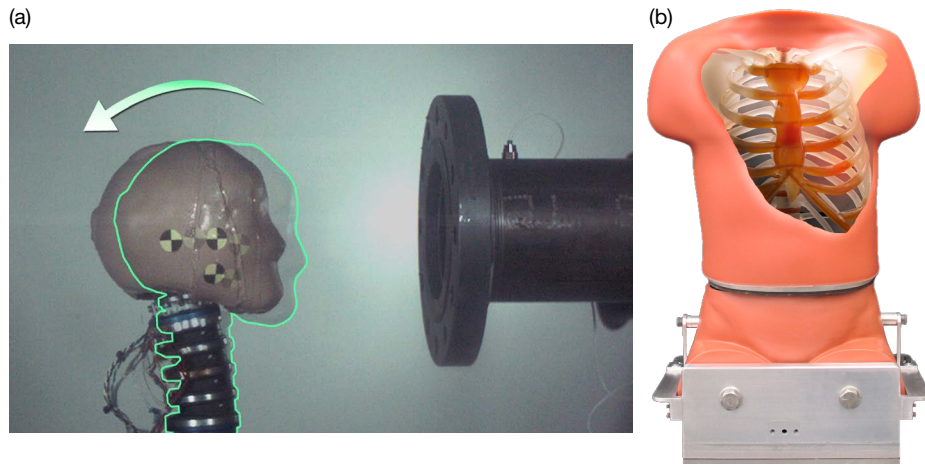
(a)

(b)

Figure 2. APL contributions to research in biomechanics and warfighter injury mitigation. (a) APL shocktube for assessing the impact of blast on a surrogate headform and (b) instrumented biofidelic torso model for injury assessment.

contributed significant knowledge to research communities. Figure 2 shows blast impact testing using APL's shocktube and a torso model to support measurement of various forces on the human body.

The most well-known program that emerged through APL's biomedical business area was the Revolutionizing Prosthetics (RP) program,[19] a bold Defense Advanced Research Project Agency (DARPA) initiative to develop an anthropomorphic, neurally integrated and controlled upper extremity prosthetic for wounded warfighters. Within the first 6 months of the program, APL led a team to develop an initial prototype that more than doubled the number of powered motions in a prosthetic arm and included haptic (touch) feedback. Over the 15-year program, APL brought together more than 30 organizations to mature the technology and build the Modular Prosthetic Limb (MPL), creating the world's most dexterous prosthesis.[20] Neural research culminated in collaborative experiments with the University of Pittsburgh and the California Institute of Technology enabling paralyzed subjects to use neural implants to control the MPL and receive touch feedback directly to the brain, while studies at various Johns Hopkins institutions demonstrated individual finger control could

be achieved through a neural interface.[21] For amputees, rewiring nerves through targeted muscle reinnervation and osseointegrated bone implants for attaching the prosthesis (coupled with wireless sensors and machine learning algorithms) enabled "thought-based" control without brain implants.[22] Accomplishments of the RP program made national and international news, as the world witnessed the first-ever neurally controlled, integrated prosthetic limb via major news programs and outlets such as *60 Minutes* and CNN. Figure 3 shows Johnny Matheny, the first subject to work with the MPL via osseointegration, and Jan Scheuermann, who was featured on *60 Minutes*[23] using her mind to control the MPL.

TODAY

As the successful biomedical technology development efforts at APL continued to have significant impact, leaders at APL and JHM discussed the degree to which APL should engage more broadly at strategic levels in the medical community. Although the Institute of Medicine and National Academy of Engineering

(a)

(b)

Figure 3. Milestones of the Revolutionizing Prosthetics (RP) program, a DARPA initiative to develop an anthropomorphic, neurally integrated and controlled upper extremity prosthetic for wounded warfighters. (a) Johnny Matheny, the first subject to work with the MPL via osseointegration, with the osseointegrated MPL. (b) Jan Scheuermann during a visit to APL. Jan was featured on *60 Minutes* controlling the limb with her mind.

reports in the early 2000s highlighted the imperative to apply engineering principles to health care systems, more than 10 years later, deaths in the United States due to preventable medical errors were still estimated to be over 250,000.[24] In 2012, a partnership between APL and JHM's Armstrong Institute for Patient Safety and Quality focused on demonstrating the ability to apply systems engineering in a health care setting to reduce preventable medical errors. Project Emerge (Figure 4), funded by the Gordon and Betty Moore Foundation, highlighted the effectiveness of integrating data and systems in an intensive care

Figure 4. Project Emerge system concept. The system centers on a tablet application that displays integrated data from the various information systems and patient monitoring equipment used in an intensive care unit (ICU). The application's "harms monitor" seeks to reduce the occurrence of seven common preventable harms facing ICU patients by tracking whether preventative measures have been taken.

unit to improve clinicians' awareness of patients at risk for preventable medical harms. This project demonstrated the utility and value that proven systems engineering approaches could bring to health care.

Recognizing the enormous opportunity to address this and other health care challenges by leveraging APL's deep expertise in systems engineering, APL leadership made the decision to stand up what became the Lab's 12th mission area. Its vision is to revolutionize health through science and engineering. With the establishment of the National Health Mission Area in 2016, APL and JHM embarked on a journey to redefine health care through the application of systems engineering principles and the targeted development and integration of technology solutions.

Since that time, the partnership between JHM and APL has grown stronger and is poised for significant impact. Through active discussions regarding the biggest barriers to better leveraging the vast amounts of data within JHM, leaders across APL and JHM worked to define the first project that would be funded through a combination of APL and JHU funding and would have the potential to transform medicine and patient-centered care. Under the umbrella of the Johns Hopkins Precision Medicine initiative, the Precision Medicine Analytics Platform (PMAP)[25] was conceived as a project that would enable researchers and clinicians to make better use of all available patient data within JHM. This project—focused on building the infrastructure required to integrate disparate data sources from across JHM and developing advanced analytic tools to generate new insights into patient diagnosis, prognosis, and treatment—has become a focal point across JHM

for data aggregation, integration, and analysis. With $12.5 million in funding over 5 years, APL engineers and data scientists, working closely with JHM faculty and clinicians, are developing and deploying the first platform available enterprise-wide for data sharing and data analytics at scale across Johns Hopkins. See the article by Ravitz, in this issue, for more on PMAP.

APL and JHM have established numerous additional partnerships to further scientific understanding of the causes of illness, injury, and disease, and to develop transformational advancements in the delivery of care through the application of a holistic, systems approach to health care. Partnerships currently exist between APL and almost every division and department in the JHM/School of Medicine enterprise.

When the novel SARS-CoV-2 coronavirus began emerging in Wuhan, China, in December 2019, another set of collaborations across APL and Johns Hopkins began to take hold. Beginning with a partnership to turn a research initiative to track the outbreak into a global platform that would soon become the most accessed site for tracking the coronavirus disease 2019 (COVID-19), the JHU COVID Dashboard, APL and Johns Hopkins researchers worked tirelessly to integrate the world's data on COVID cases and to make the data and analytical results available across the globe. With billions of site visits per day, the JHU COVID Dashboard has become one of the most recognized systems for global situational awareness and would not have been possible without the partnership between APL and Johns Hopkins. Many other collaborations around COVID-19 were rapidly underway by the spring of 2020, including genomic sequencing of COVID-positive samples, design and development of new

ventilator prototypes, and an array of rapid-prototyping activities to develop and deliver personal protective equipment to frontline health care workers.

APL also played a critical role in the US national response activities beginning in March 2020, serving as the lead organization supporting the White House Data and Analytics Task Force, which continues to support national decision-making regarding resource allocation and COVID-19 forecasting. Key experts from across the Johns Hopkins enterprise have been integral members of the response team, creating and refining epidemiological models to support the most critical decisions facing the country.

APL's broader activities across the health domain continue to embrace the Lab's mission as a university-affiliated research center and its military roots serving significant programs for the Army, Navy, Marine Corps, and joint agencies, including the Defense Health Agency. These include programs to further our understanding of the sources of musculoskeletal injuries and improved protection systems. Significant systems engineering efforts such as the Warrior Injury Assessment Manikin (WIAMan),[26] which aims to develop a biofidelic manikin that can measure the force that is translated to the musculoskeletal system during an under-vehicle blast event, is a hallmark program APL has led for the Army. And major sustained efforts for Navy sponsors, including the Bureau of Medicine and Surgery (BUMED), focus on medical operational readiness, taking advantage of APL's systems engineering and operations analysis expertise. APL's development and implementation of a seminal value-based care framework for BUMED[27] was an industry leader in applying a new theory of integrated care, received strong praise from the surgeon general of the Navy, and was described in the *New England Journal of Medicine: Catalyst* as an exemplar implementation of value-based care.

New lines of effort within the Department of Health and Human Services (HHS) also hold promise to address broader population health challenges. Activities sponsored by the Centers for Disease Control and Prevention (CDC) within HHS aim to anticipate and mitigate emerging infectious diseases, while data analytics and other communications expertise are applied to responding to health threats in disaster scenarios.

Nontraditional partnerships with industry and foundations are also critical to revolutionizing health. While DOD sponsors the development of cutting-edge technologies for military and national security challenges, health and health care technologies often emerge through industry-funded research and development activities. Through funded efforts driven by the health and technology sectors, APL is developing bold new capabilities that have the potential for game-changing impact in our understanding and treatment of health challenges.

FUTURE

APL has embarked on a bold journey to revolutionize the way health and health care are imagined, designed, developed, and integrated into the lives of individuals, systems, and populations. An abundance of data and devices that measure various parameters associated with health provide enormous opportunities to integrate and leverage the information to empower individuals to remain healthy. Through development of sensors that measure new vital signs of health, models to put those measures into the context of a healthy baseline, and continuous measurement for early identification of deviations from a healthy baseline, APL envisions a future that transforms the way individuals and systems approach health. Key research efforts are focused on developing novel, noninvasive optical sensing technologies that address critical clinical challenges in neurological health, including brain swelling, intracranial hemorrhage, seizure, and neural tissue degradation. Several life-threatening health challenges are currently being tackled through research and development activities supporting the US Army and other sponsors.

When medical care is required, all available data and relevant information should be used to inform a comprehensive approach to provide the right care to every individual at the right time. This can be accomplished through rigorous systems engineering and integration efforts that focus on the individual, not the health system, at the center of the health ecosystem. Through research and development activities funded by the US Army, APL is developing a medical device interoperability reference architecture that incorporates autonomous capabilities to provide prolonged field care in battlefield settings. Key to the success of these activities is expertise in artificial intelligence, systems engineering, and autonomous systems.

At global scales, APL will continue to focus on novel measures, integrating disparate data sources at individual and population scales, and applying new analytic methods to provide widespread situational awareness about potential outbreaks and other health threats. Building on legacy capabilities developed by APL, like the Electronic Surveillance System for the Early Notification of Community-based Epidemics (ESSENCE), the Lab seeks to develop a platform that allows for global data aggregation, analysis, and insights to support key decision-making in advance of emerging pandemics. Critical research and development activities supporting the CDC and other US government sponsors are underway to help move this vision forward. This will proactively enable resilience and facilitate timely and effective response across populations to ensure that health is maintained even through major events. As we continue learning from the COVID-19 outbreak, the challenges we must overcome to achieve our envisioned future become more clear. Figure 5 represents APL's

Figure 5. Envisioned futures of APL's National Health Mission Area. Programs seek to predict and prevent illness, injury, and disease; rapidly detect and respond to changes in health status; restore and sustain health; and improve overall health and human performance—leveraging expertise from across Johns Hopkins and APL to develop solutions that advance health and health care for civilian, military, and veteran populations worldwide.

envisioned future for national health. (See the article by Gregg, Nichols, and Blackert, in this issue, for more on the envisioned futures initiative.)

Over the next several years, APL will work to strengthen trusted partnerships with key DOD and broader US government sponsors and stakeholders. Working together, we will seek to ensure that our military, veteran, and civilian populations have the most capable technologies to prevent injury, illness, and disease and, when prevention is not possible, that any changes in health status are immediately detected and treated with appropriate interventions. These relationships, coupled with partnerships with industry and JHM, position APL to continue making game-changing contributions to national health challenges. The partnership between APL and JHM has never been stronger and holds great promise for developing groundbreaking technologies, implementing life-saving solutions, and redefining the way we envision personalized and population-level health and care.

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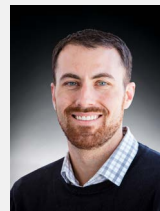
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