Smart Bioelectronics: The Future of Medicine is Electric

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Abstract
There is an opportunity for dramatically increased synergy between electronics and biology, fostered by the march of electronics technologies to the atomic scale and rapid advances in system, cell, and molecular biology. In the next decade, it may become possible to restore vision or reverse the effects of spinal cord injury or disease; for a lab-on-a-chip to allow medical diagnoses without a clinic or instantaneous biological agent detection. Bioelectronics is the discipline resulting from the convergence of biology and electronics and it has the potential to significantly impact many areas important to the nation’s economy and well-being, including healthcare and medicine, homeland security, forensics, and protecting the environment and the food supply. Not only can advances in electronics impact biology and medicine, but conversely understanding biology may provide powerful insights into efficient assembly processes, devices, and architectures for nanoelectronics technologies, as physical limits of existing technologies are approached. Advances in bioelectronics can offer new and improved methods and tools while simultaneously reducing their costs, due to the continuing exponential gains in functionality-per-unit-cost in nanoelectronics. Realizing the promise of bioelectronics requires research that crosses disciplines, such as electrical engineering, biology, chemistry, physics, and materials science. Bioelectronic medicine is a new field but the hope and promise is significant. Bioelectronic medicine is not an innovation but a revolution. Its concept is simple: use an electrical current to trick the body into healing itself. Bioelectronic medicine holds the promise of treating a variety of diseases and illnesses.

Keywords: Biosensors, Bioelectronics

INTRODUCTION
Bioelectronics was defined as 'the use of biological materials and biological architectures for information processing systems and new devices'. Bioelectronics, specifically bio-molecular electronics, were described as 'the research and development of bio-inspired (i.e. self-assembly) inorganic and organic materials and of bio-inspired (i.e. massive parallelism) hardware architectures for the implementation of new information processing systems, sensors and actuators, and for molecular manufacturing down to the atomic scale'.[1] The National Institute of Standards and Technology(NIST), an agency of the U.S. Department of Commerce, defined bioelectronics in a 2009 report as "the discipline resulting from the convergence of biology and electronics".[2]

Sources for information about the field include the Institute of Electrical and Electronics Engineers (IEEE) with its Elsevier journal Biosensors and Bioelectronics published since 1990. The journal describes the scope of bioelectronics as seeking to: "... exploit biology in conjunction with electronics in a wider context encompassing, for example, biological fuel cells, bionics and biomaterials for information processing, information storage, electronic components and actuators. A key aspect is the interface between biological materials and micro- and nano-electronics."

Biosensors are defined as analytical devices incorporating a biological material (e.g. tissue, microorganisms, organelles, cell receptors, enzymes, antibodies, nucleic acids, natural products etc.), a biologically derived material (e.g. recombinant antibodies, engineered proteins, aptamers etc) or a biomimic (e.g. synthetic receptors, biomimetic catalysts, combinatorial ligands, imprinted polymers etc) intimately associated with or integrated within a physicochemical transducer or transducing microsystem, which may be optical, electrochemical, thermometric, piezoelectric, magnetic.

Treating human disease with electrical impulses dates back decades and now pharma is exploring the concept of ‘electroceuticals’ to complement drug-based therapy. The harnessing of electrical stimulation to treat human disease dates back to the 19th century and the work of Guillaume Duchenne, who is considered the pioneer of electrophysiology.
Imagine a world without rheumatoid arthritis, Crohn's disease, asthma, obesity, Alzheimer's, and lupus? Every day, close to a billion people suffer from these inflammatory diseases. They pump their bodies full of drugs and live their lives in constant fear of what's to come.

When tech and medicine meet, everyone benefits. The tech doesn't have to be a new MRI or laser printed organs, either — even the lowly bandage can benefit from an upgrade. Different researchers worldwide are using their particular expertise to develop a host of newer, smarter, more effective bandages; many of which are steadily making their way out of the lab and into the real world.

There is a high demand for a non-invasive, rapid, and highly accurate tool for disease diagnostics. Recently, smart bioelectronics (saliva based diagnostics) for the detection of specific biomarkers has drawn significant attention since the sample extraction is simple, cost-effective, and precise. Compared to blood, saliva contains a similar variety of DNA, RNA, proteins, metabolites, and microbiota that can be compiled into a multiplex of cancer detection markers. The salivary diagnostic method holds great potential for early-stage cancer diagnostics without any complicated and expensive procedures. Here, we review various cancer biomarkers in saliva and compare the biomarkers efficacy with traditional diagnostics and state-of-the-art bioelectronics.

Representative bioelectronic systems for each group are summarized based on various stages of a cancer. Systematic study of oxidative stress establishes the relationship between macromolecules and cancer biomarkers in saliva. We also introduce the most recent examples of salivary diagnostic electronics based on nanotechnologies that can offer rapid, yet highly accurate detection of biomarkers. A concluding section highlights areas of opportunity in the further development and applications of these technologies.

CONCEPT OF MECHANISM OF SMART BIOELECTRONICS

Given that practically all of the body's organs and functions are regulated through neural circuits communicating via electrical impulses, it should theoretically be possible to interpret the electrical language of diseases. By extension, it could be possible to stimulate or inhibit the malfunctioning pathways with tiny electrodes in order to correct the defect. This micro-manipulation of the nervous system - targeting impulses (action potentials) to specific cells within neural circuits - could conceivably be exploited to manipulate a broad range of bodily functions, such as controlling appetite or blood pressure or stimulating the release of insulin in response to rising blood sugar.

Strategy to isolate the nerve bundles sending efferent signals involved in specific diseases from the peripheral nervous system to the brain, and blocking them will likely involve an invasive procedure. The strategy of blocking the afferent signal from being released in the brain will have a broader impact. Some following important area

- Understanding molecule/cell-electronics interfaces;
- Understanding cellular responses—and their variabilities—to stimulation (electrical, mechanical, chemical, thermal, and the like);
- Ability to collect and analyze essential data on the state of biomolecules and cells (chemical, physical, structural, functional);
- Ability to monitor, in real-time, the biochemistry of a single cell or a population of cells, which requires comprehension of interaction between molecules;
- Ability to deliver appropriate therapeutic materials and stimuli in real-time; and
- Ability to detect, identify, and quantify thousands of different biomarkers simultaneously.

ROLE OF REGULATORS

The urgency to provide a safe, effective and affordable treatment for pain without the dangers of narcotic and non-steroidal anti-inflammatory drugs should be a major factor in the FDA taking prompt and positive action.

News and activities on active medical implants and wearable devices to monitor, affect and modify functions of the body. New e-health platforms in recent aim to integrate the growing range of apps and wearable devices
that track everything from calorie-burn to fertility cycles. A new technology uses electronic pulses to treat ailments without exposing the body to surgical risks or toxic side effects.

Figure1: Magic: Implant prevents spleen sending out chemicals that attack own body

WORLD LEADERS IN BIOELECTRONICS

a) Bioelectronics Corporation: BioElectronics Corporation is a leader in non-invasive electroceuticals and the maker of an industry leading family of disposable, drug-free, pain therapy devices: ActiPatch® Therapy, over-the-counter treatment for back pain and other musculoskeletal complaints; RecoveryRx® Devices for chronic and post-operative wound care; Allay® Menstrual Pain Therapy; and HealFast® Therapy for dogs, cats and horses.

b) ElectroCore Medical: ElectroCore Medical which is rolling out a non-implanted device called GammaCore that stimulates the vagal nerve as a means of treating cluster headache and migraine in Canada, Germany, the UK and other parts of Europe. The non-invasive device is also being developed for other indications such as epilepsy, asthma, irritable bowel syndrome and even Alzheimer's disease.

NOVEL APPROACHES IN FLECTROCEUTICALS

a) Design of Electronic Medical Devices by Wirelessly Transfer Power: Stanford engineers have developed a way to wirelessly transfer power deep inside the body, and to use this power to run minute electronic medical devices. And it further highlighted the possibility that this technology could provide a path toward a new type of medicine that allows physicians to treat diseases with electronics rather than drugs.

b) Handheld device by ElexroCore(US company): ElexroCore has developed a handheld device that treats migraine headaches with electronic pulses instead of drugs.

c) Dubbed Electroceuticals Or Bioelectronics: Dubbed the GammaCore, the device looks like an electric razor and is placed against the neck, where it stimulates the vagus nerve. The electronic pulses help control a substance called glutamate which has been linked with migraines.

APPLICATIONS

- New generation of programmable microimplants-sensors to monitor vital functions deep inside the body; electrostimulators to change neural signals in the brain.
- Drug delivery systems to apply medicines directly to affected areas.
- ActiPatch outstanding effectiveness of participants' use of the devices for back, knee and other muscle and joint pain for a range of medical conditions including osteoarthritis, rheumatoid arthritis, fibromyalgia, sports injuries, and post-surgical pain.
The applications of this approach are intuitive for central nervous system (CNS) diseases, but could be even more widespread in light of research which suggests stimulation of certain nerve fibres can boost the immune response. Harnessing that potential could bring cancer and potentially even infectious diseases into the electroceutical spectrum.

ADVANTAGES OVER OTHER MEDICINE
- Treatments is more effective than drugs because electroceutical approaches would implant devices near specific brain circuits to directly modulate their activity.
- ActiPatch addresses a large unmet medical need and provides a safe efficacious new therapeutic modality to mitigate the devastating side effects of drug treatment.

FUTURES PROSPECTIVES
- Venture fund should be dedicated to bioelectronics with the aim of developing “the first medicine that speaks the electrical language of the body” by the end of this decade.
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Multifunctional Endoscope

Figure 2: Multifunctional endoscope systems lasers with theranostic nanoparticles (NPs)–therapy
A scientific team from the Center for Nanoparticle Research within the Institute for Basic Science (IBS) has developed a multifunctional endoscope that integrates transparent bioelectronics such as lasers with theranostic nanoparticles (NPs)–therapy to test new medication and tailor a unique treatment plan for a patient.
Conventional endoscopes lack the spatial resolution necessary to detect and treat small cancers and other abnormalities. They are equipped with a flexible tube fitted with a camera, lens and light delivery system, providing both maneuverability and direct visualization of the gastrointestinal tract. However, despite the proven utility of current surgical endoscopes, onboard sensors coupled with treatments are unavailable because of the macro-scale size of the conventional system, preventing diagnosis and therapy of micro-scale tumors.

Multifunctional endoscope systems have the potential to reduce the procedure time and improve the efficiency of minimally invasive surgical procedures for colon cancer treatment. Furthermore, efficient therapy can contribute to the excellent oncologic and economic yield for various gastrointestinal cancers or precancerous lesions in the future. (Hyunjae Lee et al. An endoscope with integrated transparent bioelectronics and theranostic nanoparticles for colon cancer treatment, Nature Communications (2015). DOI: 10.1038/ncomms10059)

Bioelectronic medicine may trick body into healing itself

Imagine a world without rheumatoid arthritis, Crohn's disease, asthma, obesity, Alzheimer's, and lupus? Every day, close to a billion people suffer from these inflammatory diseases. They pump their bodies full of drugs and live their lives in constant fear of what's to come. Bioelectronic medicine is a big idea. And it's not some future sci-fi story, This is happening now. Bioelectronic medicine is a new field but the hope and promise is significant.

Figure 3: Bioelectronic medicine holds the promise of treating a variety of diseases and illnesses

Bioelectronic medicine is not an innovation but a revolution. Its concept is simple: use an electrical current to trick the body into healing itself. Bioelectronic medicine holds the promise of treating a variety of diseases and illnesses. But how do you go from the hope of improving lives to the device that actually makes it happen? That work happens at the labs at the Feinstein Institute on Long Island.

Bio-Electronic Band aids

A team of researchers from Tufts, Perdue, Harvard, and Women’s Hospital, supported by the National Science Foundation is, working on a new kind of bioelectronic smart bandage. The team introduced a bandage that uses sensors, biomaterials, and microsystems tech to monitor and treat wounds that require longer-term care, such as diabetic ulcers and burns.

Preemptive care in bandaging

One team out of UC Berkeley, also supported by the NSF, is working on a bandage that detects tissue damage before it even becomes visible. Intended for pressure ulcers, otherwise known as bedsores, the bandage monitors the electrical changes caused by cell death. It is essentially a printed array of tiny electrodes on a thin flexible film. Bedsores can be anything but minor: Christopher Reeve died of an infection that started with a bedsore. When internal cells (not at the surface of the skin) start to die, the cell walls break down and the bandage reads the electrical signals that escape the degraded walls.
Figure 4: Bandage reads the electrical signals that escape the degraded walls

Google reveals a tiny, disposable monitor that tracks glucose levels

The Life Sciences division of Google envisions a paradigm in which sugar-monitoring contact lenses and wellness wristbands are ubiquitous. News that it’s working on a miniaturized tracker for diabetics, then, doesn’t really come as a surprise. Life Sciences’ new wearable, a sensor-laden continuous glucose monitor no larger than a bandage, is intended to supplant the painful pinprick tests that most type 1 and 2 diabetics regularly undergo. It’s inexpensive and disposable, reliable enough to measure sugar “in real time,” and will tap “advanced data analytic platforms” for contextualized reports. Flexible bioelectronics

Flexible electronics is an emerging field which encompasses design and fabrication of electronic devices and circuits on flexible polymeric substrates. Flexible bioelectronics is the application of flexible electronics into biomedical and life sciences applications for monitoring, sensing and neuroprosthetics. The new devices, known collectively as flexible bioelectronics, will do much more than deliver medicine. They will be able to monitor all the vital signs of the healing process, such as oxygen levels and temperature, and make adjustments when needed, as well as communicate the information to health professionals who are off-site. To fulfill the critical need for the devices to be flexible, the team is testing new materials, such as a hydrogel that would cover a wound with just the right amount of stretch to be comfortable.

Repair nanobots on damage patrol

Biological organisms have an amazing ability to automatically initiate self-healing and self-repair when they sustain damage. Materials engineers are dreaming about making materials that could do the same thing. Inspired by the intrinsic self-repairing ability of biological systems, researchers have developed a class of
artificial 'smart' materials-called 'self-healing materials’ – which can repair internal or external damages (see for instance: "Self-healing hybrid gel system"); more recently they even developed an approach to self-healing electronic devices ("A magnetic-assisted, self-healing supercapacitor"). Many of these approaches depend on (a limited amount of) the healing agents being incorporated into the material or on external stimuli to initiate the repair process. Complicating the matter are damages that originate at the micro- or even nanoscale, such as cracks and tears in thin-films, membranes and electronic circuits. An ideal material and device self-healing system would be autonomous: damages would be detected, localized and repair initiated independent from outside interference and without the need for external control.

Figure 5: Schematic and actual process of autonomous repair of broken electronic pathways by artificial nanomotors that autonomously seek and repair microscopic mechanical cracks to effectively restore conductivity. (A) Structure of the functionalized Au/Pt Janus spherical nanomotor. (B, C) Nanomotor-based autonomous conductivity restoration concept. Localization of nanomotors at the crack site restores a conductive pathway, lighting up the light bulb. (D, E) Time-lapse microscopy images showing the nanomotors swimming and localizing in a surface crack within 2 seconds. (F) SEM image illustrating the spherical nanomotors confined in the crack. Scale bar: 5 µm.

The team's nanomotors were inspired by the chemotaxis of neutrophils toward inflammation sites and the aggregation of platelets at the collagen fibers of a wound to stop bleeding. The catalytic nanomotors are composed of conductive gold/platinum spherical Janus particles that self-propel efficiently in the presence of hydrogen peroxide fuel. They convert this fuel into directed motion to autonomously seek the surface cracks on the substrate. "The presence of surface cracks introduce obstructions and gaps, which present both energetic barriers and potential wells to the random walk trajectories of the nanomotors," Wang explains the nanomotors’ sensing mechanism. "The surface cracks act as potential wells, which confine and localize the nanomotors. He notes that these nanomotors can also spontaneously self-assemble into clusters that can travel as groups toward the damage location.

Mouth guard could continuously monitor diabetes, and more

We've already heard about an electronics-packing mouthguard that can be used to detect serious impacts to the head. Now, scientists at the University of California, San Diego have developed one that could provide continuous readings of users' health markers including lactate, cortisol and uric acid. It may be used to monitor the well-being of people such as diabetics, to track the performance of athletes, or to detect stress in soldiers.

Developed by a team led by professors Joseph Wang and Patrick Mercier, the current version of the mouthguard is designed specifically to check wearers’ uric acid levels, which are affected by conditions including diabetes and gout.
Within a circuit board about the size of a penny, the device contains a screen-printed sensor that incorporates silver, Prussian blue ink and an enzyme known as uricase. When the uricase is exposed to uric acid in the user's saliva, it reacts by forming hydrogen peroxide, which subsequently reacts with the ink. This in turn produces an electrical signal, which is digitized and then wirelessly transmitted to a smartphone or tablet for analysis.

So far the mouth guard has proven accurate at detecting high uric acid levels in saliva samples from a patient with hyperuricemia, a condition which produces excessive uric acid in the bloodstream. It was also able to detect that those levels had gone down, when the test subject took uric acid-lowering medication.

Previously, the only way of monitoring those levels would have been through the drawing of multiple blood samples, and the patient would need to wait for symptoms to develop before knowing that they needed to take the medication.

In the lab tests, however, the saliva samples were simply spread on the sensor – the electronics need to be further miniaturized before the mouth guard can comfortably be worn continuously in a person's mouth. It is hoped that a wearable version should be complete within a year.

**Digestible batteries needed to power electronic pills**

Imagine a "smart pill" that can sense problems in your intestines and actively release the appropriate drugs. We have the biological understanding to create such a device, but we're still searching for electronic materials (like batteries and circuits) that pose no risk if they get stuck in our bodies. In *Trends in Biotechnology*, Christopher Bettinger of Carnegie Mellon Univ. presents a vision for creating safe, consumable electronics, such as those powered by the charged ions within our digestive tracts.

Edible electronic medical devices are not a new idea. Since the 1970s, researchers have been asking people to swallow prototypes that measure temperature and other biomarkers. Currently, there are ingestible cameras for gastrointestinal surgeries as well as sensors attached to medications used to study how drugs are broken down in the body.

"The primary risk is the intrinsic toxicity of these materials, for example, if the battery gets mechanically lodged in the gastrointestinal tract--but that's a known risk. In fact, there is very little unknown risk in these kinds of devices," said Bettinger, a professor in materials science and engineering. "The breakfast you ate this morning is only in your GI tract for about 20 hours--all you need is a battery that can do its job for 20 hours and then, if anything happens, it can just degrade away."

Bettinger and other researchers are exploring how minerals in a healthy diet, or even pigments from the skin or eye, could be used in bioelectronics. Ingestible devices that are used now are powered by off-the-shelf batteries, just like what you'd find in a watch. Bettinger challenges whether a segmented battery is necessary,
as the natural liquids within the body can be the electrolytes that move current through the device. Labs have already proven that electronics built using this method can disintegrate in water after two to three months. There's also evidence that manufacturing biologically inspired "smart pills" can be cost-effective and pass regulatory approval. Ingestible medical devices and even 3-D printed pills have been given the green light for patient use in recent years despite their atypical properties. Regarding cost, one of the reasons medications cost so much is that only a small percentage of a pill actually makes it to where it needs to be used in the body. Bettinger argues that if an electronic pill can make better use of expensive medications, then the amount needed for each patient can be reduced.

"There are many rapid advances in materials, inventions, and discoveries that can be brought to bear on medical problems," Bettinger said. "If we can engineer devices that get the most mileage out of existing drugs, then that is a very attractive value proposition. I believe these devices can be tested in patients within the next five to 10 years."

**3D-printed programmable release capsules**

an increasing number of 3D-printing appearing in nanotechnology applications (see for instance these recent Nanowerk Spotlights: 3D-printed graphene for electronic and biomedical applications; 3D-printed 'smart glue' leverages DNA assembly at the macroscale; or Fully 3D-printed quantum dot LEDs), researchers are expanding this fabrication technique to more and more areas.

A recent example is the introduction of a novel 3D-printing based method to produce highly monodisperse core/shell capsules that can be loaded with biomolecules such as therapeutic drugs."Our method provides us with robust control over particle properties, passive release kinetics, and particle distributions throughout a 3D matrix," Michael McAlpine, an associate professor in mechanical engineering at the University of Minnesota, tells Nanowerk. "Furthermore, we render these capsules stimuli-responsive by incorporating gold nanorods into the polymer shell, allowing for highly selective photothermal rupture and triggered temporal release of the biomolecular payload."McAlpine and his group, working with researchers from Washington University in St. Louis, published their findings in the June 4, 2015 online edition of Nano Letters ("3D Printed Programmable Release Capsules"), where they describe the use of 3D printing to hierarchically order polymers, biomolecules, and nanomaterials into hybrid functional materials in a scalable manner.

![Figure 6: Programmable printing and rupturing of capsules: (I) multiplexed arrays of aqueous cores containing biomolecular payloads are printed directly on a solid substrate; (II) PLGA solutions containing AuNRs of varying lengths are dispensed directly on the aqueous cores, forming a solid stimuli-responsive shell; (III) the capsules are selectively ruptured via irradiation with a laser wavelength corresponding to the absorption peak of the nanorods.](image)

"Our technique is enabled via the 3D-printing of multiplexed arrays of biomolecule-loaded capsules, along with tunable and orthogonal laser-triggered rupture and release of active biomolecules," Maneesh K. Gupta, a former member of McAlpine's group and now a research scientist at Air Force Research Laboratories, explains. "One can imagine filling the capsules with molecules such as drugs, nucleic acids, enzymes, growth factors, cell markers and other functional proteins, into a hydrogel ambient."Adds Fanben Meng, a postdoc researcher in McAlpines Lab and co-first author with Gupta: "The advantages of our 3D printing-based method include: 1) highly monodisperse capsules; 2) efficient encapsulation of biomolecular payloads; 3)
precise spatial patterning of capsule arrays: 4) 'on the fly' programmable reconfiguration of gradients; and 5) versatility for incorporation in hierarchical architectures."

An interesting feature of these capsules is the control of the spatial and temporal release of payloads. This is achieved by incorporating gold nanorods in the shell. Using specific wavelengths determined by the length of the nanorods, the rods can be heated which subsequently ruptures the shell. The 3D printing technique itself also provides precise control over the capsule volumes and architectures. "This work provides a promising solution to generating multiplexed spatiotemporal molecular gradients in 3D architectures, which is significant to mimic the dynamic microenvironment surrounding cells in natural tissues, as living organisms guide tissue development through highly orchestrated gradients of biomolecules that direct cell growth, migration, and differentiation in 3D matrices," notes Meng.

![Figure 7: 3D printing of hierarchically multiplexed capsule arrays.](image)

3D printing of hierarchically multiplexed capsule arrays. Top row: Schematic illustrating an emulsion ink-based method to 3D print complex capsule arrays. The emulsion ink is prepared by directly dispersing the aqueous core in the PLGA solution. The hydrogel and emulsion inks are sequentially printed in a layer-by-layer manner to form a 3D structure. Bottom row: Optical images of 3D multiplexed capsule arrays directly printed in cylindrical and square hydrogel matrices, respectively (colors of the capsules are from food dyes in the dispersed cores).

The researchers expect that this platform of 3D printed programmable release capsules will be useful in applications such as dynamic tissue engineering, 3D printed drug delivery systems, synthetic/artificial tissues, programmable matter, and bionic nanosystems. Beyond this, another important application area could be combinatorial screening of biomolecular gradients – drugs, toxins, pollutants, etc. – against cell types. A particularly far-reaching example would be to imagine having a collection of stem cells, which could be triggered using a red laser into a heart, or with a green laser into a liver. "Our work was motivated by the fact that living systems utilize exquisite control of biomolecular gradients to control cell fate and ultimately enable complex functional tissues," says McAlpine. "We believe that replicating such control is a key to many future advances in bioengineering." "There has been tremendous prior work on utilizing microfluidics, particle encapsulation, and stimuli-responsive materials to address some of these challenges," he adds. "Our findings
offer a novel perspective by offering a 3D printing based approach to solve these challenges, which has advantages in precision control over volumes, spatial distributions, and diversity of materials including nanomaterials and biomolecules. "A next stage of the investigation now requires studies regarding the biocompatibility and feasibility of using 3D printed capsules to control cell fate, from the individual cell level to the level of tissue engineering. As the team points out, beyond biological studies, there is a tremendous amount of work to be done to enhance the material and functional properties of the capsules. For example, improving the resolution and spatial alignment of these printed capsules, developing stimuli responsive shells with reversible payload release properties, and developing other approaches to stimulate the capsules, such as using electrical signals rather than light triggering. This work was funded by the NIH, AFOSR, and Intelligence Community.

CONCLUSION:
The application of electronics technology to biology and medicine is not new. Examples include pacemakers and virtually the entire medical imaging industry. Research that enabled these applications grew out of many disciplines of science and engineering; however, recently, the term “bioelectronics” is being used more widely to describe this multidisciplinary field. Science and technology experts representing the nano-electronics and biotechnology communities provided inputs for this report. Collectively, the participants identified a wide range of opportunities and challenges for the field, which are listed in the table below. The strategic drivers that were most frequently cited were: disease detection, disease prevention, and prosthetics. The technologies and devices that will enable applications in these areas will impact other vital areas, such as homeland and national security, forensics, and the environment. Progress in all of these sectors requires innovation in crosscutting areas, including measurement and characterization, fabrication, and power sources. As a next step, stakeholders from government, academic, and industry should jointly develop a detailed bioelectronics roadmap, which can serve to facilitate effective planning and resource management for increasing the productivity and commercialization of bioelectronics research and development. Such an exercise would define and clarify projected application-specific research metrics and metrology gaps and needs; timelines for research, development, and prototyping; and emerging market and commercialization insertion opportunities.

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