Towards personalized medicine: the evolution of imperceptible health-care technologies

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Abstract

Purpose – *When wearable and implantable devices first arose in the 1970s, they were rigid and clashed dramatically with our soft, pliable skin and organs. The past two decades have witnessed a major upheaval in these devices. Traditional electronics are six orders of magnitude stiffer than soft tissue. As a result, when rigid electronics are integrated with the human body, severe challenges in both mechanical and geometrical form mismatch occur. This mismatch creates an uneven contact at the interface of soft-tissue, leading to noisy and unreliable data gathering of the body's vital signs. This paper aims to predict the role that discreet, seamless medical devices will play in personalized health care by discussing novel solutions for alleviating this interface mismatch and exploring the challenges in developing and commercializing such devices.*

Design methodology/approach – *Since the form factors of biology cannot be changed to match those of rigid devices, conformable devices that mimic the shape and mechanical properties of soft body tissue must be designed and fabricated. These conformable devices play the role of imperceptible medical interfaces. Such interfaces can help scientists and medical practitioners to gain further insights into the body by providing an accurate and reliable instrument that can conform closely to the target areas of interest for continuous, long-term monitoring of the human body, while improving user experience.*

Findings – *The authors have highlighted current attempts of mechanically adaptive devices for health care, and the authors forecast key aspects for the future of these conformable biomedical devices and the ways in which these devices will revolutionize how health care is administered or obtained.*

Originality/value – *The authors conclude this paper with the perspective on the challenges of implementing this technology for practical use, including device packaging, environmental life cycle, data privacy, industry partnership and collaboration.*

Keywords *Research, Innovation, Personal health, Nanotechnology, Biotechnology, Forecasting*

Paper type *General review*

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Introduction

Our body is an ocean of physical patterns: heartbeats, respiration, muscle movements, neural activity, and many more. These patterns contain information-coded messages that can be excavated, refined and defined. To do so, we need sophisticated interfaces to effectively access and evaluate such information – yet we are only just beginning to develop the needed tools. Traditional electronics are up to six orders of magnitude stiffer than soft tissue (Liu *et al.*, 2017). As a result, when we want to integrate electronics with biology, there are severe challenges in mechanical and geometrical form mismatch. Stiffness mismatch creates an uneven contact at the interface of soft-tissue, leading to noisy and unreliable data gathering of the body's vital signs. This dichotomy in mechanical properties between traditional

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electronics and soft biological tissue causes user discomfort, which gives rise to a host of issues such as low device lifetime and low probability of public adoption. As we cannot change the form factors of biology yet, we instead have to design and fabricate conformable devices (i.e. ones that are flexible and stretchable) that have the same shape and mechanical properties to match those of soft body tissues. These devices will help us listen to our health patterns by conforming to the body, providing higher quality biometric information, achieving accurate location specificity and enabling seamless user experiences.

To gain further insights into our body, we can use these mechanically adaptive devices to collect and convert essential patterns into beneficial forms. Specifically, these devices can enable continuous real-time monitoring at the location of interest, resulting in high quality and large-scale data collection. Combining this data with signal processing and machine learning tools will drastically improve the accuracy and timeliness with which medical professionals can diagnose deviations from regular health patterns. These devices, therefore, will enhance therapy by closing the feedback loop between accurate detection of symptoms and treatment of conditions. Thus, the vital information extracted from the body using mechanically adaptive devices can change the way we do science, improve the way we monitor and protect our health and advance our ability to help others.

Wearable and implantable devices have predominantly been rigid, as they were conceived in the early 1970s, when the first hearing aid was developed (Mills, 2011). How can we bring conformability to this field? The past two decades have seen a transformation in wearable and implantable devices brought about by research efforts in both industry and academia (Koydemir and Ozcan, 2018). Still, we are just at the beginning of an era of conformable devices that started in earnest with efforts by Bell Labs and IBM Research, where researchers experimented with polymer transistors formed on bendable sheets of plastic in the late 1990's (Rogers, 2001; Kagan *et al.*, 1999). These initial experiments, although targeted towards paper-like displays, turned out to have game-changing potential for the health-care system.

However, the current wearable market is still comprised mostly of hard, bulky smartwatches, wireless headphones and smart glasses that focus on fitness tracking. These fitness metrics – such as step count and heart rate – are certainly important, but future innovations should stray from these solved problems and instead foray into an unsolved space; personalized health care. Recently, efforts in academic research labs have pioneered this field. They are pushing the forefront of wearable and implantable devices toward mechanically adaptive solutions that will unravel and translate the multitude of signals coming from the human body. These advancements include sticker-like electronics for physiological sensing (Kim *et al.*, 2011), self-powered pacemakers and biomedical sensors (Dagdeviren *et al.*, 2014; Dai *et al.*, 2003) and minimally invasive localized drug delivery systems for the brain (Dagdeviren *et al.*, 2018).

In the upcoming sections, we describe two major necessities for developing and commercializing mechanically adaptive devices. These devices must:

- conform to the human body; and
- decode its variety of patterns, i.e. seamlessly extract and interpret its biological information.

Following these prerequisites, we forecast the following three key aspects for the future of mechanically adaptive biomedical devices, detailing how this technology will have an impact in various sectors:

1. changing the way we “do science”;
2. revolutionizing health care; and
3. harvesting energy for self-powered devices.

We conclude this article with our perspective on the challenges of implementation, including device packaging, environmental life cycle, data privacy, industry partnership and collaboration.

Conforming to the human body

The human body is soft and curvy, while traditional electronics are stiff and bulky. To overcome this severe mechanical mismatch, we fabricate materials, whether traditional or novel, to bend, stretch, and twist into arbitrary shapes. Currently, there are two main strategies to develop conformable devices:

1. creating new structures by thinning down existing, rigid materials; or
2. using newer, composite materials, which are inherently mechanically compliant, in existing structures (Rogers *et al.*, 2010).

The first approach involves using hybrid structures that push the limits of traditional semiconducting materials. In these configurations, the hard material defines the active function, while the soft material defines the shape and mechanics. For instance, bonding hard ultrathin silicon films to soft elastomers creates artifacts that are more resistant to deformations. This method mimics how rigid aluminum can be made flexible and adaptable to a variety of surfaces by drastically reducing its thickness. Beyond traditional electronic materials, composites present another viable option. For example, organic semiconductors and elastomer-based conducting nanocomposites, albeit not as high performing as silicon, are highly conformable and increasingly functional. Together, these two strategies form the basic building blocks for developing bio-electronic devices with enhanced conformability.

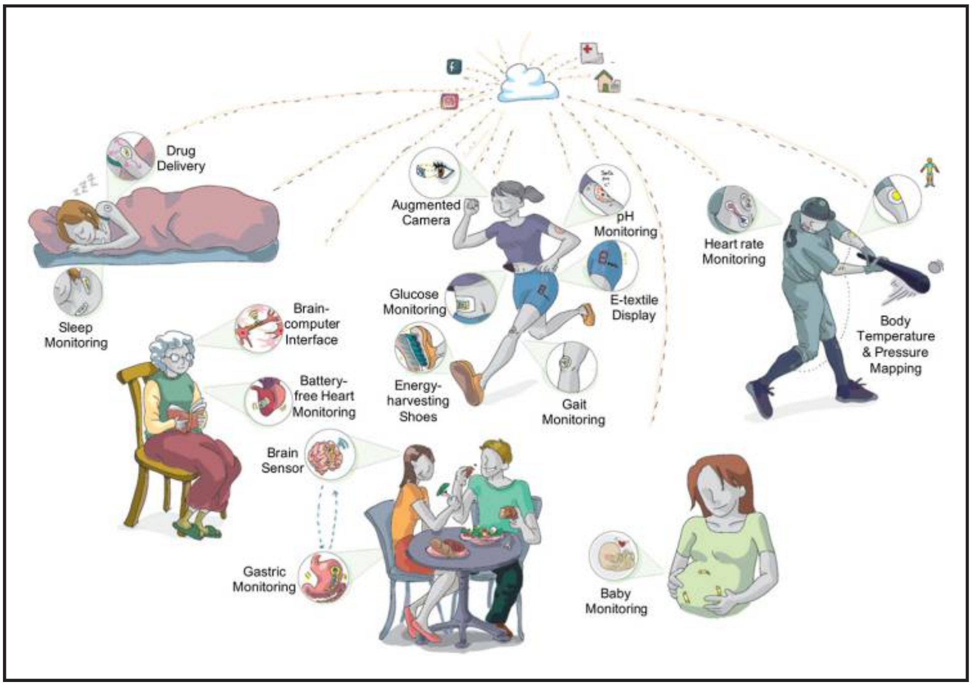
Decoding signals from the human body

In conjunction to conformability, it is essential to further develop methods for interpreting the collected information. Application of signal processing and machine learning techniques will help us extract useful patterns from these datasets, ultimately increasing our ability to monitor our health condition. In a recent demonstration, conformable devices were used to measure heart rates from professional baseball players in the USA. The data generated used machine learning methods, and hence, revealed key insights on the athlete's performance and vital signs during gameplay (Lee *et al.*, 2018). In addition, researchers have demonstrated the feasibility of creating an entirely wireless, full-body sensor network (WBSN) for accurate spatio-temporal mapping of temperature and pressure (Han *et al.*, 2018). The large amount of data generated from these sensor networks would be incomprehensible without the proper analysis techniques. With the appropriate models, however, the raw pressure data from the aforementioned WBSN's can be translated to predict skin ulcers (Grap *et al.*, 2017; Cox *et al.*, 2016; Behrendt *et al.*, 2014). Indeed, interpretive and predictive decoding techniques, when paired with conformable devices, will allow us to translate our bodily signals with an unprecedented level of precision and accuracy (Figure 1).

Changing the way we "do science". Thus far, we have described the importance of both conforming and decoding as the two key pillars of electronics for health-care applications. These seamless electronic devices have the profound potential to directly alter many aspects of scientific research, ranging from access to information to the ability to ask new questions.

Biomedical research is unique, in that it leverages advancements of diverse fields such as electronics and materials science. Traditionally the problems pursued in this field have been limited by the tools made available to the medical researchers. Testing in these fields is often a cumbersome, lengthy process that is carefully constructed to protect patient safety and mitigate risks. Bringing a biomedical device or new pharmaceutical to market

Figure 1 Imperceptible health-care technology applications in daily life



can take between seven to twelve years on average and the process requires extensive resources (Reichert, 2003). By providing researchers with new tools for examining the human body, conformable devices may alter our methods of scientific inquiry by allowing us to acquire greater quantities of high-quality information, conduct human studies outside of the laboratory or hospital environments and probe environments that were previously inaccessible – such as the soft tissue of the human brain or the complex structure of the gastrointestinal tract (i.e. the "gut"). Scientists can now even prototype extremely realistic physical models of individual organs to conduct testing on, before interacting with actual patients (Murphy and Atala, 2014). Therefore, we can begin to re-contextualize these tools as helpful extensions of the human body for scientific researchers, by reducing barriers to information.

Current medical studies involving patients often require extensive, costly instrumentation that is difficult to use, reducing patient compliance (Haynes and Dantes, 1987). This significantly limits the scope of medical exploration. Unintrusive, comfortable, self-powered devices that can be worn for up to a few weeks will allow researchers to bring their studies out of the lab environment and into people's homes (Choi *et al.*, 2018). Continuous monitoring is extremely useful for pre-clinical studies in cases like chronic implants, understanding relationships between human behavior and health, and tracking fetal health during gestation. Researchers such as John Rogers (Kim *et al.*, 2011), Zhong Lin Wang (Kim *et al.*, 2011; Fan *et al.*, 2012) and Muhammad Mustafa Hussain (Nassar *et al.*, 2016) have fabricated devices intended for such purposes robustly and affordably. As researchers overcome existing barriers to manufacturing, these devices will become ubiquitous and scientists can broadly use them in natural contexts, rather than in artificial environments such as research laboratories. These types of devices can be easily deployed to the masses, allowing continuous collection of biometric data from millions of people through distributed data collection. Such a tremendous amount of data, used ethically, will help researchers to exponentially expand the reach of their work beyond what is currently feasible. The so-called "big data" generated by conformable devices will conceive a disruptive new wave of predictive models for early disease detection, well-informed hypothesis testing around medical issues, and better, more personalized diagnosis of deviations in health. For example, presently, to understand individual sleep patterns, researchers must bring patients to an overnight laboratory stay (i.e. removing them from their standard environment) which can create an intrusive and unpleasant user experience (Kingshott and Douglas, 2000). Moving toward conformable devices, however, will enable us to collect data within the framework of daily routines, to truly understand human behavior such as during sleep.

The impacts of these devices is not limited to wearables; the soft mechanics of such systems will also allow us to probe locations that were previously inaccessible. One of the most promising areas that these tools can elucidate is the human brain (Canales *et al.*, 2015; Minev *et al.*, 2015). Cellular scale conformable electronic implants can potentially resolve complications from rigid brain probe studies that often lead to unintended secondary consequences altering auditory or gustatory perception (Cyron, 2016). Additionally, these conformable devices provide high spatial resolution and controlled stimulation of damaged brain areas in a localized fashion. Hence, in pre-clinical settings, such conformable devices can be particularly impactful in deciphering the relations between neural connections and cognition.

Another interesting application space is the integration of current advances in high-resolution imaging and molecular genetics with flexible integrated electronics. This work can help researchers understand various underlying neural networks and their impact on the physiology and behavior of individuals. A noteworthy advance in this regard was made by Park *et al.* (2015) wherein they demonstrated a soft, stretchable, wirelessly powered LED implanted in freely-behaving mice, configured for optogenetics experiments. Similarly, Minev *et al.* (2015) recently developed e-dura, a stretchable spinal cord implant that mimics living nervous tissue. The fully functional device, with stretchable active components for electrical and chemical stimulation at the point of injury, was implanted in paralyzed rats and evoked minimal immune response. Applying these conformable devices such as the stretchable LED and e-dura will significantly aid the way neuroscientists relate cognition to neuronal activity and in the development of novel tools for understanding disease.

As another instantiation of how conformable decoders are changing the methods of scientific inquiry, Dagdeviren *et al.* (2018) and Ramadi *et al.* (2018) developed a fully rollable and ingestible piezoelectric sensor that can be swallowed. Upon ingestion, the sensor unfolds along the stomach lining and measures the rhythmic contractions of the membrane. This can enlighten us with information about our bodily functions based on data collected in one of our most important, yet barely understood, organ systems: the digestive tract. Taking the research further, in clinical settings, such sensors can help gastroenterologists diagnose disorders of the gut.

Conformable devices have even begun to impact our food. John Rogers collaborated with Michael McAlpine, David Kaplan and Fiorenzo Omenetto to develop edible silk-based sensors to detect food quality and environmental information using fully digestible materials (Tao *et al.*, 2012). Bonacchini *et al.* (2018) further developed ingestible electronics that can not only monitor food, but also aid in therapy and diagnosis inside the digestive system. Real-time probing of the complex processes of the digestive systems has been difficult, but ingestible devices can allow us to test elaborate hypotheses in their intended environments. Devices and concepts such as these equip the research community with invaluable tools that will empower them to investigate more challenging basic science questions.

If such bioelectronic wearable and implantable devices become more accessible and enable new modes of studying both human behavior and physiology inside and outside of the lab environment, researchers can collectively approach larger, more complex scientific inquiries. By probing complex environments, researchers can develop a comprehensive understanding of the human body. Beyond that, the ubiquity of these devices will allow individuals to have ownership of their personal information. Accordingly, society can collectively approach medical questions from a systemic level. As expanded upon in the following sections, we can therefore explore continuous monitoring of health, leading to personalized medicine.

Revolutionizing health care. Under our current health-care system, people must go to hospitals and wait in long lines to get health checkups done. The current health-care system is analogous to the pre-cellphone era in which people waited in long lines outside public telephone booths to make calls. Today, people simply take out their personal phones to text or call whenever they desire. Conformable on-body (i.e. wearable) and in-body (i.e. implantable) health-care devices will allow us to advance to the "cellphone era" of health care so people will have immediate and real-time access to their health-care information, e.g. vital signs and nutritional levels.

We envision that conformable device technology will impact health care in three key ways:

1. By using conformable technologies, electronic devices will be placed everywhere in and on the human body. For example, neural lace (Strickland, 2017), a thin injectable mesh (Liu *et al.*, 2015), can be implanted in the brain to monitor brain health. Neural lace can also electrically stimulate the brain to control symptoms of Parkinson's disease (Statt, 2017). As discussed previously, the gut, often referred to as the "second brain" (Gershon, 1999), will no longer be an uncharted territory as ingestible devices will track gut health using biocompatible technologies. Additionally, heart problems will no longer be intractable due to self-powered implantable sensors that can control abnormal heart rhythms (Dagdeviren *et al.*, 2014; Ma *et al.*, 2016). Thus, using comfortable devices, we can get real-time, complete and personalized information about our bodies.

2. Using wearable and implantable devices, doctors will have access to a complete set of health measures to continuously monitor people's health over time. As of now, human health is reduced to a few numbers, such as weight, body mass index (BMI) and blood pressure, but health care needs to focus on people's holistic physical, mental, and emotional well-being. Conformable devices will allow us to monitor user's electrophysiological signals to decipher their emotional health (Picard *et al.*, 2001). Devices like Empatica Embrace and E4 can already measure user's emotional states through their heart rate and electrodermal activity (EDA) (Li and Chen, 2006), but Empatica's devices are neither flexible nor self-powered and therefore, not convenient for everyday use. By evaluating user health-care data based on an individual's overall physical, cognitive, and emotional health, doctors will have a comprehensive picture of an individual's health.

3. Conformable sensors will give us access to a wide range of health measurements in real-time so we can evaluate the immediate impacts of our decisions, such as by using real-time glucose sensors (Koh *et al.*, 2016) to determine which foods cause a spike in our glucose levels. As a result, we will be able to adjust our lifestyles accordingly. In our everyday lives, it is difficult to evaluate the effects of actions on our health since we do not have access to real-time and continuous information regarding our bodies. Currently, people observe the long-term accumulated effects of their activities, such as lung cancer due to smoking, and by this point, the effects are impossible to reverse. With conformable sensors, people can observe the real-time impact of unhealthy activities on their body to proactively address issues. Real-time health-care information will also enable healthy habit formation due to the rapid positive feedback loop. Hence, real-time and personalized information will give individuals access to information so they can rationally make the decision to improve their behaviors and optimize their health.

As conformable devices usher us into the "cellphone era of health care", people will gain access to their personalized and holistic health-care information. Doctors will be able to continuously and remotely monitor their patients to make better decisions about people's health. Continuous access to health information will also encourage people to improve their habits, promoting preventive rather than reactive health care. Compared to our current curative health-care model, preventive health care is a more sustainable health-care model for our resource-constrained society. Therefore, conformable devices will empower individuals, health-care professionals and society as a whole to better manage human health.

Harvesting energy for self-powered systems. Technological advances have allowed humans to collect and transfer health-based information across the globe in seconds, harness energy from beating hearts and track and visualize data. Yet, wearable and implantable electronics devices still rely on outdated, traditional power sources and batteries. Batteries are often the heaviest and bulkiest components in medical devices, and their rigidity often clashes with the curvilinear nature of our body. In addition, common batteries are made from lithium polymers, containing substances that are highly toxic to human health and pollute the environment upon fabrication and disposal.

The usable duration of wearable devices is truncated by the lifetime of the battery: we use them for a specific activity and then we need to take them off and recharge the battery. For implantable devices, the case is even more severe: patients that use implanted pacemakers to regulate arrhythmias need to undergo surgery every five to seven years to replace the batteries. If we are to build devices that conform to the human body and decode our body's signals, we also need to find ways to continuously supply energy sustainably.

A promising approach is to use energy from within: the human body is full of opportunities to harvest energy for self-powered devices and autonomous electronics (Wang, 2008; Dagdeviren *et al.*, 2017; Dagdeviren *et al.*, 2016). Our body continually produces kinetic energy. From footsteps, joint movements, muscle stretching, blood flow, to the contraction of the heart, lungs and diaphragm, these internal and external mechanical energies can be harvested through nanogenerator-based conformable devices. For example, at the time our heel strikes the ground when walking, we generate around 67 Watts of power (Starner, 1996). Harvesting even 1-5 per cent of that power would be enough to run many body-worn devices, such as mobile phones (Qi *et al.*, 2010). There are two main categories of nanogenerators: piezoelectric and triboelectric. Piezoelectric nanogenerators (PENG) transform mechanical to electrical energy and vice versa via the piezoelectric effect, converting stress or strain on a material to electric charges and potential. On the other hand, triboelectric nanogenerators (TENG) produce electricity from mechanical energy through a combination of electrostatic induction and contact electrification due to friction between different materials. Despite many hurdles in research, the future of nanogenerators is still promising. It is currently one of the fast-growing fields in novel energy harvesters with an exponential growth of research outputs over the years (Li *et al.*, 2017). Flexible PENG devices that can intimately conform to the surface of the heart (Dagdeviren *et al.*, 2014) or the gastrointestinal tract (Dagdeviren *et al.*, 2017) and harvest energy from their contractions, for example, could be used to power body implants such as a cardiac pacemaker (Dagdeviren, 2016). Coating a TENG layer on threads and embedding the TENG threads into a fabric or a shoe could also independently power wearable electronics, through the kinetic energy harvesting from body movements, such as walking and running (Wang *et al.*, 2016; Zhu *et al.*, 2013).

Several efforts have also been conducted to harvest biochemical energy from the glucose of internal body biofluid (Hansen *et al.*, 2010) and sweat lactate secreted during human perspiration, both using biofuel cells (Jia *et al.*, 2013), as well as bacteria in saliva via microbial fuel cells (Mink *et al.*, 2014). A working prototype of fully functional self-powered ingestible devices has been recently demonstrated (Nadeau *et al.*, 2017). These devices use a biocompatible galvanic cell that can power an ultra-low-power sensing, drug-delivery, and wireless transmission electronic from stomach acid in a capsule form-factor. Furthermore, there is a constant temperature gradient on the skin interface between the human body and the ambient air, which can be harvested by wearable thermoelectric generators (Leonov and Vullers, 2009). The aforementioned conformable energy-harvesting devices can be tailored to various wearable and implantable electronics based on their specific application, location and power requirement. Conformable energy harvesters will help us take a step towards a self-sustainable ecosystem of on skin and implantable electronics for the human body.

Perspectives

Research on conformable devices has come a long way since their inception in the 1990's. Market analysis indicates that the market size for printed, flexible, and organic electronics will grow by 2.5 times in the next 10 years (Das and Harrop, 2013). Currently, stretchable electronics make up a small segment of this field, however, as they emerge from R&D, they have an immense growth potential. Additionally, yearly patent registration data corresponding to printed electronics was fitted to a growth curve (Yoon *et al.*, 2014). It was found that starting in 2013, technological developments of printed electronics have entered the maturity stage, with a remaining life of 8.5 years in this phase prior to commercialization. Although the field of conformable electronics has grown steadily for two decades, there remain challenges to be addressed, specifically regarding environmental impact, data protection and privacy, manufacturing and scale-up, and formation and fostering of collaborations.

Environment

As systems and processes are developed to fabricate devices that aid in understanding our own internal well-being, it is equally important to be careful not to destroy our external environment. Researchers should optimize every step of the design process to create methodologies that are truly sustainable. In realizing this goal, we should tend to minimize harmful processes and/or materials from the development stream, and focus on abundant materials rather than those that are difficult to acquire (Kirchain *et al.*, 2017). Another venue could be transient electronics which can dissolve at the molecular level in target medium (Dagdeviren *et al.*, 2013; Hwang *et al.*, 2012). By optimizing the materials used and engineering the dissolution of the devices, the environmental impact of electronics can be greatly minimized.

Data privacy

Privacy and access to data are important issues that many stakeholders face and should care about. As memory storage takes extra power, the data collected in electronic devices is typically sent wirelessly to a computer interface for analysis using a data acquisition system. The collection of massive datasets requires the critical examination of matters of privacy. A crucial component of this examination stems from an understanding of where this data is collected from and how it is used. For example, health patterns reveal deep insights about our daily activities, and we may very understandably want to keep these patterns private, sharing only at our own discretion. The implementation of these devices, therefore, requires rigorous efforts to protect the consumer. Users must be assured that their sensitive health information is only shared with their doctors and not with third parties such as insurance companies. It is key that scientists and policy makers come together to make laws and required policy that ensure data privacy while avoiding overprotection that hinders technological development (Data overprotection, 2015). By establishing data-protection laws and policies, we could avoid data scandals such as the 2018 incident involving Facebook, Inc. (Aziza, 2018). Together with data collection and the essentials for law foundation, the field would move forward in coming years.

Industry

There are many barriers to industrialization of these new technologies. Often, device reliability and durability are not high enough in comparison to existing technologies. Sometimes, development costs are simply too high due to challenges of mass fabrication and deployment that do not significantly allow lower costs compared to research lab fabrication methods (Sevilla *et al.*, 2014). Mass production of products such as in Shenzhen, China, however, does promise to fasten the progression of conformable electronics (Lindtner *et al.*, 2015). By designing devices with industrial considerations in mind, researchers can facilitate the process for commercializing important technologies with lifesaving abilities and advantages for humanity (Rojas *et al.*, 2014). For example, the first demonstration of voice recognition was in 1982 in industry; however, it was only in recent years that this technology has become mainstream in our phones, after more academic research. Many prominent researchers in the field, such as Zhong Lin Wang, acknowledge these sentiments (Lai *et al.*, 2017), and others such as Muhammad Mustafa Hussain are exploring much cheaper device fabrication methods to expedite the industrialization process (Nassar *et al.*, 2016) of comformable devices.

Collaboration

We should also guarantee that our society and policies are aligned with our technological advancements. Rather than reactively evaluating the interplay between the government, society, and research, researchers can play a vital proactive role in approaching these developments by connecting all of the relevant stakeholders. In the spirit of fostering conversations across many sectors, engineers and doctors should collaborate to ensure that they are approaching the problem from multiple relevant perspectives. By sharing the intellectual property and resources, establishing strong relationship between researchers in industry and academia is a key step to developing sustainable and achievable scale-up manufacturing process. Elon Musk's Neuralink is leading this effort by promising to make their IP open source and by making design considerations with massive scale-up in mind (Minev *et al.*, 2015).

Scientists should work closely with their intended user base to truly understand their needs, and policymakers have to converse with academics and scientists to respond to the immense potential disruptions. This collaborative environment is reflected at the MIT Media Lab and its membership consortia with dozens of companies. The Media Lab goes beyond boundaries in known disciplines by promoting an anti-disciplinary culture that combines seemingly different research areas. With the financial support of the member companies, researchers at the lab dive into unanswered questions that can fundamentally change the way people live, communicate and engage with the world. The established financial and technological nature of the industry perfectly complements the scarcity of resources academic research faces. As the field evolves, we encourage consideration regarding the impact that bioelectronic medical technology may have on human life, and the role that each individual and organization can play in this evolution.

Conclusion

We have come a long way in terms of technologies that allow us to 'listen' to the human body. The stethoscope was man's first attempt at listening to the beating heart with a physical device. Now we have electrocardiography machines that continuously monitor human heartbeats, yet we still have humans attached to a machine with cumbersome wiring. To gain further insights into the human body, we need conformable devices that can live on or in the human body and invisibly merge with the user to help decode human health in a real-time, continuous, seamless and effortless manner. At the MIT Media Lab, we believe that the best way to predict the future is to actually make it. To realize this vision of a better future, we combine media, arts and sciences. Thus, in this paper, we have highlighted attempts towards a future of conformable devices for health care, and underscored the ways in which those conformable devices will radically change the face of human health care and personalized medicine for the better. In our next paper, we will take a comprehensive look at the impact of conformable devices on not just health care, but also on fashion, art and music, infrastructure and transportation, climate and space exploration.

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