Skin sensors are the future of health care

Thin, flexible, wireless monitoring systems could make medicine more predictive and personalized, argue Shuai Xu, Arun Jayaraman and John A. Rogers.

Thin, soft electronic systems that stick onto skin are beginning to transform health care. Millions of early versions of sensors, computers and transmitters woven into flexible films, patches, bandages or tattoos are being deployed in dozens of trials in neurology applications alone; and their numbers growing rapidly. Within a decade, many people will wear such sensors all the time. The data they collect will be fed into machine-learning algorithms to monitor vital signs, spot abnormalities and track treatments.

Medical problems will be revealed earlier. Doctors will monitor their patients’ recovery remotely while the patient is at home, and intervene if their condition deteriorates. Epidemic spikes will be flagged quickly, allowing authorities to mobilize resources, identify vulnerable populations and monitor the safety and efficacy of drugs issued. All of this will make health care more predictive, safe and efficient.

Where are we now? The first generation of biointegrated sensors can track biophysical signals, such as cardiac rhythms, breathing, temperature and motion. More advanced systems are emerging that can track certain biomarkers (such as glucose) as well as actions such as swallowing and speech.

Small companies are commercializing soft biosensor systems that measure clinical data continuously. These include Vital Connect in San Jose, California; iRhythm in San Francisco, California; MC10 in Lexington, Massachusetts; and Sibel Health in Evanston, Illinois. For example,
Interfaces that create skin

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Surgery. They are currently still expensive,

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require attention.

Biomarkers. All the flexible sensor systems

range of measurements must improve. And

they have done their job, just as a wound

patches might melt away harmlessly after

the electronics for years or decades. Some

manufacturing ultra-thin layers that protect

developing biocompatible materials and

primates. Practical challenges include

demonstrating how hard their foot hits the

in several African countries, including

where infrastructure is lacking. We will

trial our biosensors in maternity clinics

in several African countries, including

Zambia, Kenya and South Africa, later this

year, in partnership with the non-profit

organizations the Bill & Melinda Gates

Foundation and Save the Children. The

patches will track physiological data such

— from accelerometers, gyroscopes, micro-

fluidic sensors, and electrocardiographs and

electromyographs (which measure

activity in the heart and muscles,

respectively). To improve data quality, these

sensors should be sited on the best places

on the body to collect information — for

example, electrocardiogram signals should

be recorded on the chest, not the wrist. Gait

is better assessed with sensors on the ankles.

Noise will need to be filtered out, and
decisions will need to be made about whether

it is better to stream all of the data to the

cloud or process some of them on the chip

and transmit only key parameters or insights

extracted from the base data, in the form of

warnings or notices.

Interpretation. Digital dashboards need
to be developed to allow physicians and

patients to track outputs, log changes and

make clinical decisions. Machine-learning

models need improvement, for example to

predict how long it will be until a patient is

discharged from hospital or is able to walk

or feed themselves safely without assistance.

Long-term monitoring in the community

would help physicians to assess the evolu-

tion of stroke recovery, Parkinson's disease

and other disorders.

Behaviour. More needs to be learnt about

how patients use biosensors in their every-
day lives. If people are to wear the devices

for weeks or months, the patches will need
to look acceptable, and ideally attractive.

They should be comfortable and maintain

good contact with the skin during washing

or exercising. Although some sensors are

now small enough fit on a fingernail and

thin enough not to show through clothing,

they will need to become yet smaller and

thinner.

CLINICAL PRACTICE

Bringing these technologies to patients will

take action on three more fronts: validation,

regulation and data protection.

To speed up their entry into the clinic,

soft biosensors must target unmet medi-
cal needs, such as mental-health monitor-
ing in the home. Changes in vital signs

and in neuroendocrine, neurotropic and

inflammatory biomarkers could yield

insights that are unavailable to clinicians
today. Signs of social isolation and loneliness

might prompt a visit from a carer or a call

from a loved one.

Wireless health monitoring could also

revolutionize health care in countries

where infrastructure is lacking. We will

trial our biosensors in maternity clinics

in several African countries, including

Zambia, Kenya and South Africa, later this

year, in partnership with the non-profit

organizations the Bill & Melinda Gates

Foundation and Save the Children. The

patches will track physiological data such

as physical activity, blood pressure and

respiratory rate in women and their babies
during pregnancy, warning of complica-
tions such as fetal hypoxia or an impending

haemorrhage.

Therapies. Interfaces that create skin

sensations, such as vibrations, might

enhance rehabilitation, notably with speech

and motion therapies. Drugs could be deliv-

ered through skin patches, as they are already

for motion sickness (scopolamine), pain

(fentanyl), contraception (noretgestromin

and ethinylestradiol) and high blood pres-

sure (clonidine). The release could be trig-

gered electrically, acoustically or thermally,

for example, by applying heat to a polymer

pocket. Sensors could also deliver electrical

or thermal stimulation to treat neurological

disorders or modulate pain.

Implants. Soft sensor systems could be used

inside the body. A thin, flexible implant

might be wrapped around the heart or spine
to monitor and stimulate it. Demonstration

versions of thin, flexible technologies that

track the electrical activity of the brain have

been tested in mice, cows and non-human

primates. Practical challenges include

developing biocompatible materials and

manufacturing ultra-thin layers that protect

the electronics for years or decades. Some

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TO-DO LIST

Biomarkers. All the flexible sensor systems

approved by the US Food and Drug Admin-

istration (FDA) so far collect biophysical sig-

nals. Biochemical signatures, such as glucose

or hormone levels, are hard to glean without

puncturing the skin with needles.

Some emerging devices collect fluid by

inserting a filament into the skin. And detect-
ing chemicals in sweat is a promising alterna-
tive. Sweat contains many indicators relating to

cell health and organ function (such as elec-
trolytes), the immune system (cytokines) and

drug interactions (metabolites). Sweat sensors

are being developed that capture chloride,

glucose, lactate, urea, creatinine, alcohol, pH

and even heavy metals. Quantifying protein

and hormone levels in sweat would increase

these sensors' applicability further.

Still, sensors need to be able to collect and

analyse sweat without it becoming

contaminated or degrading, and they will

also require new chemical tests and types

of assay.

Tools. Imaging and spectroscopy capabili-
ties would allow for real-time assessments

of the body. Examples are optical coherence
tomography, confocal microscopy, Raman

spectroscopy and two-photon excitation

microscopy. If such systems could be mini-

aturized, they could diagnose skin tumours

without the need for a biopsy sample or

surgery. They are currently still expensive,

bulky and wired.
Regulatory approval is crucial, and challenging to obtain. Hardware is largely covered by existing frameworks; algorithms are not. But there are encouraging signs that software applications can be regulated. In the past few years, the FDA has approved machine-learning technology for the diagnosis of diabetic retinopathy, the first pill with an embedded sensor (Abilify MyCite) and an app to treat opioid-use disorder (reSET-O). The FDA’s pre-certification programme allows medical software from certain trusted developers to be deployed before formal evaluation.

Regulations must adapt quickly, as the boundaries between devices, data, software and therapeutics continue to blur. Special attention should be paid to clinical areas of highest need and minimal risk — there are some such within rare diseases, paediatrics, women’s health and gerontology.

Data security must be a top priority, particularly for patient information. The US Health Insurance Portability and Accountability Act established guidelines for the confidential handling of patient information in 1996. But this was well before the explosion in mobile devices and wearable sensors. New frameworks are needed. Patients must own their own data. And great care must be taken to ensure that companies do not exploit medical data for commercial gain without approval, or drive a division between those who can and cannot access this technology.

Given the poor track record of private companies in protecting consumer privacy, leadership at both the national and international level is needed. Policies must prevent employers and insurers from discriminating against people with particular data profiles, much as the US Genetic Information Non-discrimination Act of 2008 protects workers. Deviations should be met with serious financial and legal punishments.1

It remains to be seen how these sensor systems will be paid for, and how doctors will be reimbursed for interpreting and acting on the data. Still, health-care funders should champion biointegrated sensor systems because they can potentially improve the quality of care and lower costs. This fits with the move towards value-based care in the United States, where health-insurance companies and government plans such as Medicare are selecting treatments on the basis of efficacy rather than simply reimbursing services.

ROAD AHEAD
Technical progress will require close collaborations between materials and device engineers, data scientists and medical professionals. Users and carers need to be more closely involved.

Interdisciplinary funding from government sources, corporate investments and charitable foundations will be essential for collecting proof-of-concept data before devices can be commercialized. For example, the Michael J. Fox Foundation in New York City has grant programmes focused on wearable technologies in global health.

Companies need to improve manufacturing processes for devices that combine hard skeletal components and soft tissue-like materials. Yields and throughputs need to be improved to assure quality and lower costs. Automated tools are needed to design the layout and topology of circuits and mechanical components.

The effort will be worth it: bio-integrated sensors have the potential to transform nearly every aspect of medicine.

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S.X. and J.A.R. declare competing financial interests: see go.nature.com/2lxv2t for details.