Perspective



# AI-Enabled Wearable and Flexible Electronics for Assessing Full Personal Exposures

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https://doi.org/10.1016/j.xinn.2020.100031



**Research on the exposome has been extended to personal exposures, and full assessment of personal exposures is of great significance for personal health monitoring and epidemiological studies. Compared with static measurement instruments, wearable sensors are more suitable for dynamic personal exposures assessment. The development of flexible wearable sensors with the features of being physically comfortable and easy to use can be a promising solution for the measurement of personal exposures. With the support of big data and AI, large-scale personal exposures assessment could foster the transition from population-based to individual-based epidemiological studies and upgrade the intelligence level of medical services.**

Currently, over seven billion humans live on this planet, and individuals are simultaneously exposed to multifactorial stressors during their daily life. Regardless of the natural or artificial environments, changes in physical or chemical conditions in the environment may affect human health. Investigations of adverse health effects and their etiology, as well as suggestions for a healthier lifestyle, require an assessment of multifactorial personal exposures. The concept of the exposome was developed to assess the impact of multi-environmental exposures on the development of epidemiology.[1] For example, it has been proved that urban air pollution can adversely affect the health of citizens. To assess the impact of the exposome on human health, some government projects have been initiated, for instance, the Human Early Life Exposome (HELIX) initiated in Europe.[2] Sensor technology is the key fundamental entity to measure the exposome. In particular, intelligent wearable sensors, which are also called smart wearable sensors, can acquire, process, store, and transmit the electric signals generated by physical and/or chemical changes occurring in the environment, making them excellent recorders of personal exposures. Moreover, the development of wearable sensors makes it possible to assess local and dynamic personal exposures.[3] Several advancements have been reported based on the development of multi-functional devices, particularly wearable and flexible electronics,[4,5] in healthcare monitoring. However, the higher the number of sensors, the higher the requirements for both physical comfort and ease-of-use, which are difficult to achieve using the traditional silicon-based sensors. By wearing multi-functional flexible sensors, personal exposures and physical activities of individuals can be monitored,[5] including larger movements, such as bending of elbows and legs, and smaller movements, such as heartbeat, breathing, swallowing, blood pressure, and muscle vibration. Moreover, with the support of artificial intelligence (AI) and big data,[6] the effect of multi-personal exposures could be assessed, and personal physical health management can be optimized.

As a product of epidemiological studies, the exposome is a complement of the genome and refers to the measurement and assessment of environmental exposures over the course of a lifetime. Non-genetic exposures can be generally divided into three categories: internal, specific external, and general external. To clarify further, the specific external exposures refer to radiation, environmental pollutants, acoustic noise, heat stress, PM2.5, and so forth.

Traditionally, the exposome was measured by monitoring stations located in public areas; however, it is also theoretically plausible to assess exposome by integrating a wide range of individual exposures using portable devices. Static measurement equipment still remains the primary method of measuring environmental exposures, which plays an important role in evaluating public health. However, it cannot assess exposures of individuals, which may be dynamic considering the mobilities of individuals.

Wearable sensors are currently in a state of infancy, with more complex technological benefits than static measurement equipment, but they provide opportunities to assess different local and dynamic personal exposures for health monitoring. Recent studies have already tested the use of various wearable sensors embedded in smartphones, wristbands, or belts to assess personal exposures and the corresponding biological responses, such as temperature, acoustic noise, brightness, GPS, pulse, and breathing, as illustrated in Figure 1.

To fully utilize wearable sensors to record dynamic personal exposures at small scales, there are still some issues that need to be addressed, of which the most important are ease-of-use and physical comfort; here, ease-of-use is the biggest concern for individuals. Flexible electronics, which refers to fabricating organic/inorganic materials on flexible substrates, stimulate the development of flexible wearable sensors. These are attributed to the development of materials sciences, and flexible sensors with different sensing principles have been reported, including piezoresistive, capacitive, piezoelectric, electroluminescent, and triboelectric sensors, that can be used to detect different kinds of personal exposures and physiological activities of individuals. To convert external stimuli into electrical signals, lots of flexible sensing materials have been investigated, such as nanoparticles, nanowires, carbon nanotubes, 2D materials, organic materials, or directly engineering new structural constructs from established materials. In particular, most of the large variety of 2D materials have shown great potential in flexible wearable sensors.[5,7] Compared with sensing materials, the choice of substrates is more limited. The most common flexible substrates are, e.g., polydimethylsiloxane (PDMS), polyimide (PI), and polyethylene terephthalate (PET). Regarding the fabrication technology of flexible sensors, the most important point is the preparation of the sensing component, which usually requires nano-fabrication techniques, and common approaches are chemical vapor deposition, thermal evaporation, spin coating, e-ink printing, and so forth. Among the many applications of flexible electronic sensing, the most widely studied type is electronic skin, which imitates human skin to feel external temperature, humidity, and tactile stimuli.[6] Textile-integrated sensors are also great candidates for personal exposures sensing; they integrate conductive yarns and sensing elements into textiles by conventional textile production processes. Textile sensors have been used for health monitoring, such as monitoring of breathing rate and movements, and electrocardiographic and electromyographic measurements.[7] In addition, the development of flexible,

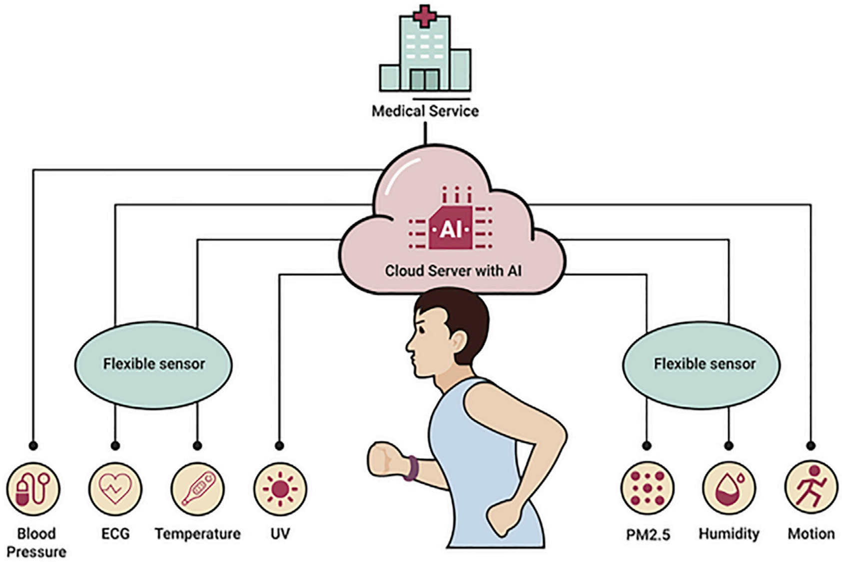


**Figure 1. Assessing Personal Exposures with AI-Enabled Flexible Sensors**

transparent, and conductive films-based electronics not only provides the chance to fabricate display devices but also wearable environmental sensors, for instance, a wearable, flexible, and transparent gas sensor that monitors exhaled gas to reflect environmental contaminant level or human physiologic status.[8] With the features of being thin, highly integrative, and physically comfortable, flexible wearable sensors are promising candidates against traditional silicon-based sensors. However, monitoring personal exposures using flexible wearable sensors is a long-term and large-scale project, which requires flexible sensors with strong durability. As a consequence, more flexible sensing materials and devices on substrates that could achieve mass production need to be developed, and the manufacturing process should be simplified and standardized as much as possible.

Integrating personal exposures can have a considerable impact on the development direction of the health condition of patients. Personal exposures of patients include the following: living habits, diet, exercise, and daily schedule. Against the backdrop of patient consent, comprehensively monitoring personal exposures of patients is significant in medical diagnosis and epidemiological studies. By evaluating the personal exposures of patients, doctors can promptly provide suggestions and administer interventions with a scientific basis to assist patients' rehabilitation. In addition, with the support of AI and big data, assessing large amounts of personal exposures can also promote data intelligence in hospitals. Besides their use in hospitals, similar technologies can also be applied to monitor the daily lives of patients at home or in the office. In recent years, the development of computer GPU hardware technology and Internet of Things has enabled the widespread application of AI algorithms in the field of healthcare. For example, deep-learning models used for diagnostic tasks have achieved physician-level accuracy, natural language processing has been successfully used in electronic health records, and deep reinforcement learning could be used in robot-assisted surgery.[9] The training of AI models often consumes large amounts of computing resources, making it difficult to be implemented on portable devices at present. However, with the promotion and construction of 5G, cloud computing services with powerful computing capabilities would become available on the mainstream. However, one of the main challenges that still exists is the lack of high-quality datasets for training AI models. Also, challenges associated with having people feel comfortable with providing personal data would make validation of the data difficult and reduce confidence in the results of the data.[10] As a result, the premise of large-scale collection of personal exposures data is to ensure the security of personal data, which apparently requires the joint progress of technology and social law.

At present, the developments of novel wearable sensors and AI algorithms can greatly contribute to the collection of data of the human exposome and foster the transition from population-based to individual-based epidemiological studies; and meanwhile a comprehensive study on the measurement of personal exposures based on wearable and flexible sensors by considering dietary characteristics, exercise patterns, and daily habits will have significant value in personal health monitoring. Large-scale AI-enabled personal flexible wearable sensors would be significant in upgrading the intelligence level of medical services.

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## ACKNOWLEDGMENTS

This work was supported by the National Key R&D Program of China (grant no. 2016YFC1402504), and also the Fund of Advanced Innovation Center of Big Data Precision Medicine of Beihang University. Dr. G.C. Shan would like to thank Prof. C.T. Liu at the City University of Hong Kong for their stimulating insightful discussions and Mr. Zichen Xu, one artist for the figure drawing support.

## DECLARATION OF INTERESTS

The authors declare no competing interests.