THE CHALLENGE FOR INDUSTRIAL HYGIENE 4.0

A NIOSH Perspective on Direct-Reading Methodologies and Real-Time Monitoring in Occupational Environments

BY EMANUELE CAUDA, JOHN SNAWDER, ANDREA SPINAZZÈ, ANDREA CATTANEO, JOHN HOWARD, AND DOMENICO CAVALLO

Direct-reading methodologies and real-time monitors will play a crucial role in workers' health and safety in the context of the Fourth Industrial Revolution. This article proposes that these technologies and other advancements will lead to a new stage of industrial hygiene, which may be called IH4.0.

The Fourth Industrial Revolution is a way of describing the blurring of boundaries between the physical, digital, and biological worlds. There are several definitions for this revolution, but they all recognize the critical importance of data. Everyday life is already affected by data generated in different environments, some occupational and some not. The impact of data will become even more significant in the future, considering the characteristics of what is known as "Big Data." These characteristics are the high *volume* of data; the elevated *velocity* with which the data is generated; the *variety* of data of different natures; and the usefulness or *value* of collecting and modeling data.

IH4.0: OPPORTUNITIES AND CHALLENGES

Even as IH4.0, industrial hygiene will continue to be organized according to the principles of anticipation, recognition, evaluation, and control (AREC). But like many other workplace activities, such as production, management, and quality control, industrial hygiene will be revolutionized by data. The profession has an opportunity and a responsibility to evolve because of a new understanding of data.

Direct-reading methodologies and real-time monitoring technologies based on sensors will allow industrial hygienists to monitor conditions in multiple occupational areas at more advanced levels. This will require the design and adoption of a new IH4.0 framework.

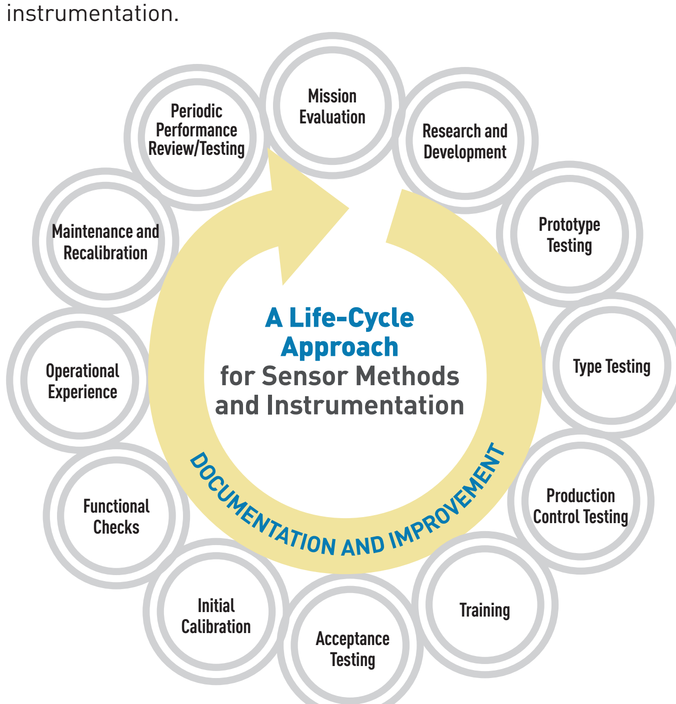
Monitoring the workplace environment combined with the adoption of wearable sensors to monitor workers' biological and physiological conditions (biomonitoring) will allow for advanced personalized exposure assessments. Ultimately, these activities can be included in a single IH4.0 strategy that exploits the benefits of new technologies while considering their limitations. It is not difficult to imagine that these technologies will generate a high volume of data at a velocity that was not even imaginable a few years ago. As explained in a November 2020 paper published in the *Annals of Work Exposures*, the different natures and connotations of these approaches and their associated data will require the development of advanced mathematical models to extract information. The outcome will be the generation of more comprehensive and multifaceted knowledge. Identifying and studying the objectives for monitoring will be two critical parts of the IH4.0 strategy, and without them, the industrial hygienist will be simply overwhelmed by data.

One common concern related to the adoption of direct-reading methodologies and real-time monitors is the challenge of using the sensors' data for compliance verification activities. This concern is generally associated with the fact that these technologies measure a secondary metric—for example, they monitor the aerosol concentration in an environment where the concern is crystalline silica—or have an accuracy lower than laboratory reference methods. This concern can be overcome by the adoption of a new mindset in which the direct-reading methodologies and real-time monitors are complementary, not alternative, tools to traditional approaches based on sample collections and laboratory analysis. The new IH4.0 framework will combine, not compare, complementary approaches to pursuing a common goal. Although some technologies cannot be used as reference instrumentation for regulatory purposes, they can be adapted for more specific applications to improve exposure assessment by obtaining an enhanced spatial-temporal resolution. Combined with improved wearability and adaptability to different types of applications, these techniques can contribute to elevating exposure assessment studies to a higher level of detail, as explained in a paper published in a June 2021 issue of the journal *Sensors*.

The technological evolution of direct-reading methodologies and real-time monitors supports their adoption in the IH4.0 framework. This is the case for technologies to monitor gases and vapors, aerosols, noise, and even more challenging physiological conditions such as fatigue, heat stress, ergonomics, and biological responses. Sensors are becoming smaller, more precise, more sensitive, and more adaptable. There are also great expectations for wearable technologies in occupational health and safety and industrial hygiene.

On one hand, wearable technologies will allow worker exposure monitoring or worker health monitoring on a

Figure 1. Life-cycle approach for sensor methods and instrumentation.



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greater scale than ever before. These technologies will be adopted for both exposome and total or cumulative workers' exposure activities. However, wearable technologies will provide the most impact if used in combination with other field-based methodologies and laboratory techniques, as described previously.

There will be challenges to address in adopting direct-reading methodologies and real-time monitors within the IH4.0 framework. For example, larger amounts of data will increase the need to focus on the ethics of personal monitoring and the management of workers' personal information, especially if used within the frameworks of Total Worker Exposure or Total Worker Health. Data generated by these technologies will need to be transferred, stored, and handled by appropriate systems, and the standardization of data and contextual information will be even more important to allow for comparison between different environments and conditions.

The interaction between technology and workers will also present challenges as well as opportunities. Workers will be increasingly in contact with these technologies, and their acceptance of sensor technologies will be critical. Overall, direct-reading methodologies and real-time monitors will be an integral component of risk communication, and this aspect has already been studied.

RESOURCES

ACS Sensors: "Wearable Chemical Sensors: Present Challenges and Future Prospects," **bit.ly/bandodkar-sensors** (May 2016).

American Society of Civil Engineers: "Enhancing Construction Safety Monitoring through the Application of Internet of Things and Wearable Sensing Devices: A Review," ASCE International Conference on Computing in Civil Engineering 2019, **bit.ly/awolusi-review** (presentation by Ibukun Awolusi, Chukwuma Nnaji, Eric Marks, and Matthew Hallowell, June 2019).

Annals of Work Exposures and Health: "Future Prospects of Occupational Exposure Modeling of Substances in the Context of Time-Resolved Sensor Data" (November 2020).

Applied Ergonomics: "A Forecasting Framework for Predicting Perceived Fatigue: Using Time Series Methods to Forecast Ratings of Perceived Exertion with Features from Wearable Sensors," **bit.ly/hajifar-fatigue** (January 2021).

European Committee for Standardization: EN 689:2018+AC:2019, *Workplace Exposure – Measurement of Exposure by Inhalation to Chemical Agents – Strategy for Testing Compliance with Occupational Exposure Limit Values* (2019).

Journal of Occupational and Environmental Hygiene: "Occupational Exposure Monitoring Data Collection, Storage, and Use Among State-Based and Private Workers' Compensation Insurers" (June 2018).

Nanomaterials: "Evolution of Wearable Devices with Real-Time Disease Monitoring for Personalized Healthcare," **bit.ly/devices-evolution** (June 2019).

NIOSH Science Blog: "Right Sensors Used Right: A Life-Cycle Approach for Real-Time Monitors and Direct Reading Methodologies and Data. A Call to Action for Customers, Creators, Curators, and Analysts," **bit.ly/niosh-right-sensors** (May 2019).

NIOSH Science Blog: "Wearable Sensors: An Ethical Framework for Decision-Making," **bit.ly/niosh-blog-sensors** (January 2017).

Pilot and Feasibility Studies: "Formative Research to Reduce Mine Worker Respirable Silica Dust Exposure: A Feasibility Study to Integrate Technology into Behavioral Interventions," **bit.ly/haas-silica** (2016).

Sensors: "Features and Practicability of the Next-Generation Sensors and Monitors for Exposure Assessment to Airborne Pollutants: A Systematic Review," **bit.ly/fanti-sensors** (June 2021).

The Synergist: "Turning Numbers into Knowledge: Sensors for Safety, Health, Well-Being, and Productivity," **bit.ly/syn1503numbers** (March 2015).

Finally, the increased adoption of direct-reading methodologies and real-time monitors in this framework will encourage industrial hygienists to revise and rethink their role in IH4.0. Industrial hygienists will be responsible for coordinating the activities of sensor experts, data analysts, engineers, behavioral scientists, and others.

THE NIOSH CENTER FOR DIRECT READING AND SENSOR TECHNOLOGIES

In 2014, NIOSH established the Center for Excellence on Direct Reading and Sensor Technologies with the goal of conducting research on the transitional phase toward IH4.0 and, specifically, the identification and development of technologies for health and safety and industrial hygiene. NIOSH has worked for decades on the development of monitoring technologies, and the Center also focuses on several theoretical and holistic aspects of health and safety.

One of the focuses of the Center is to promote the concept of a life cycle for every field-based monitoring methodology or sensor. The idea of a life cycle (Figure 1) associated with a specific technology is not a new idea or unique to IH4.0. Considering the substantial increase in technologies being adopted, it will be essential to consider the entire process—from the evaluation of a need to the testing of prototypes, and from the training of users and workers to the use of processed data.

To help industrial hygienists engage with direct-reading methodologies and real-time monitors, the Center has developed an initiative called "right sensors used right." The process of identifying and selecting the correct technology for a certain context is becoming increasingly important. For instance, an industrial hygienist can decide to adopt a less accurate sensor to take advantage of its other characteristics and features, such as higher spatial-temporal resolution, improved wearability, and adaptability to different types of applications. The adoption of any technology must entail a comprehensive knowledge of its capabilities and limitations.

Not only must industrial hygienists maintain the "right sensors used right" approach as consumers of direct-reading methodologies and monitoring technologies, but other professionals must also be engaged. The creators of new technologies must interact in the future with IH4.0 stakeholders to understand deeply the needs, concerns, and perspectives related to new technologies. New technologies must be evaluated, tested, and verified by curators, which may be research groups at universities or national and international institutions. In pursuit of this goal, the NIOSH Center for Excellence on Direct Reading and Sensor Technologies has established collaborations with AIHA, several universities in the United States and around the world, and institutions such as the Organization for Applied Scientific Research (TNO) in the Netherlands, the Health and Safety Executive (HSE) in the United Kingdom, the University of Insubria in Como, Italy, and the Italian Association of Industrial Hygiene (AIDII).

Finally, the data generated by every technology must be processed, organized, modeled, and transformed into new information and knowledge by analysts. This last aspect relative to the transformation of data into applicable information and knowledge is the newest focus of the NIOSH Center for Excellence in support of IH4.0.

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