

RESEARCH ARTICLE

From Compliance to Prediction: Integrating Real-Time Direct-Reading Instruments into Proactive Occupational Exposure Control Frameworks

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ABSTRACT

Traditionally, the control of occupational exposures has been based on the use of retrospective sampling techniques that focus on proving that the regulatory limits are met. Although they are useful in terms of documentation, those strategies provide little ability to intervene in time or predict hazards. However, recently, with the development of real-time direct-reading-instrument (DRIs) continuous exposure measurement has been made possible and offers high-resolution data that can be used to support proactive and predictive exposure control strategies. This paper will discuss how the current compliance-focused monitoring can be changed to real-time exposure management systems. The article uses a systematic review of occupational exposure science, direct-reading aerosol instrumentation, real-time detection practices and health and safety management systems to formulate a conceptual framework that integrates DRIs in operational, tactical, and strategic decisions. The suggested framework demonstrates how real-time data streams may boost task-based exposure analysis, increase the level of control, organizational learning, and worker protection. It focuses on system integration, human factors, and governance mechanisms that are required to make real-time data meaningful use instead of a one-off measurement. The results support the idea that with the proper alignment to the accepted principles of exposure science and safety management policies, the direct-reading instruments could enable the shift of the occupational exposure control to the reactive compliance to the preventive, prevention-oriented practice.

Keywords: Occupational exposure control; Direct-reading instruments; Real-time monitoring; Exposure science; Proactive risk management; Predictive safety systems

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INTRODUCTION

Traditionally, occupational exposure control has been based on compliance-based approaches to monitoring, based on periodic testing and retrospective examination

to show compliance with occupational exposure limits. Although this method has been essential towards ensuring that the health of workers is kept, it is inherently quite proactive and in most cases, the exposure to dangerous conditions is realized once it has been exposed. With the increasing dynamism and the technological complexity of work processes, the weaknesses of time-weighted and integrated sampling methods have become more pronounced, especially in workplaces where the variability of tasks, short lived emission sources, and changing exposure profiles are common.

The new technologies in sensing have resulted in the increased freedom of direct-reading instruments (DRIs) that have the ability to deliver real-time or near real-time measurements of airborne contaminants. Comprehensive reviews of aerosol DRIs describe a broad range of instruments, measurement principles, and performance characteristics, alongside good practice considerations such as calibration, validation, and contextual interpretation (Vosburgh et al., 2022). Subsequent application-focused analyses demonstrate that DRIs enable task-based exposure assessment, rapid identification of emission sources, and immediate feedback during control implementation, thereby extending their utility well beyond traditional compliance verification (Sheehan et al., 2022).

Real-time monitoring technologies have been known as an effective safety, health, and environmental management tool, especially when timely decisions need to be made (Brauch, 2015). Pragmatic advice on real-time detection systems focuses on the importance of worker protection using alarms, trend analysis, and situational awareness on the condition that the data are analyzed in a sound exposure assessment framework (Siegel et al., 2019). Nevertheless, real-time data cannot be properly used to prevent issues, and their abilities are limited without being integrated into organizational operations systematically.

Current views in occupational exposure science suggest a greater and more systems perspective of exposure data in the prediction and prevention of health risks. Vision and strategy commentaries emphasize the necessity to go beyond a set purpose of compliance toward active exposure management that manages

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control design, process optimization, and learning of it in an organization (Harper et al., 2015; Blount et al., 2015). Empirical studies in sectors with extreme hazards, like mining, also demonstrate the potential of real-time and inventive sampling methods to be used to predict early detection and mitigation of toxic emissions, which yields the importance of predictive exposure control strategies (Soubans, 2021).

Organizational and human factors are also important in successful integration of DRIs. The adoption of technology also has the potential to affect the well-being of workers, trust and engagement, which highlights the need to integrate real-time monitoring into the existing health and safety management processes (Haas and Cauda, 2022). Such approaches as gamification-related training tools have been revealed to strengthen user awareness and successful use of complicated monitoring technologies (Visci and De Robertis, 2022).

It is on this background that this article looks at the shift towards compliance-based monitoring of exposures; to predictive, proactive occurrences of occupational exposure control. Through integration by developing new improvements in direct-reading instrumentation, practice of real time monitoring, exposure science strategy, and organizational systems, the study offers a composite framework that makes DRIs key elements of anticipatory exposure management and not independent instruments of measurement.

LITERATURE REVIEW

Evolution of Occupational Exposure Monitoring

Occupational exposure assessment has traditionally been grounded in integrated sampling and time-weighted average measurements designed to demonstrate compliance with occupational exposure limits. This compliance-oriented paradigm has played a foundational role in regulatory enforcement and industrial hygiene practice, yet it has been widely recognized as limited in its ability to capture short-term variability, peak exposures, and task-specific risk conditions. Early professional discourse emphasized that delayed analytical results constrained timely intervention and reduced the practical utility of exposure data for real-time risk management (Brauch, 2015).

Within exposure science, scholars have increasingly argued for a broader and more dynamic role for exposure data, one that extends beyond documentation toward prevention, systems learning, and anticipatory control. Strategic commentaries highlight the need to integrate exposure measurements into decision-support processes that operate across temporal and organizational scales (Harper et al., 2015; Blount et al., 2015). This intellectual

shift provides the conceptual foundation for the growing interest in real-time and near-real-time monitoring technologies.

Direct-Reading Instruments: Technologies and Good Practices

Direct-reading instruments (DRIs) represent a major technological advancement in occupational exposure monitoring by enabling continuous or near-continuous measurement of airborne contaminants. Comprehensive reviews of aerosol DRIs categorize instruments according to measurement principles, such as optical particle counting, light scattering, and photometric methods, while also addressing performance characteristics, detection limits, and sources of measurement uncertainty (Vosburgh et al., 2022).

The literature consistently emphasizes that the effective use of DRIs depends on adherence to good practice principles, including calibration, instrument validation, maintenance, and contextual interpretation of data. DRIs are sensitive to environmental conditions, particle characteristics, and interference effects, making professional judgment essential for meaningful application (Vosburgh et al., 2022). Rather than replacing traditional methods outright, these instruments are positioned as complementary tools that enhance temporal resolution and situational awareness.

Applications of Direct-Reading Instruments in Exposure Control

Application-focused studies demonstrate that DRIs provide substantial value in task-based exposure assessment, source identification, and evaluation of control effectiveness. Real-time data enable practitioners to link exposure peaks to specific work activities, materials, or process conditions, thereby supporting targeted interventions (Sheehan et al., 2022). Such capabilities are particularly valuable in complex or dynamic environments where exposure determinants vary rapidly over time.

Guidance documents further illustrate how real-time detection systems can be used to establish alarms, support worker decision-making, and provide immediate feedback during high-risk operations (Siegel et al., 2019). These applications extend beyond compliance verification, enabling exposure monitoring to function as an active component of hazard control strategies rather than a passive reporting mechanism.

Real-Time Monitoring in High-Risk and Complex Environments

Evidence from high-risk industries reinforces the importance of real-time and spatially resolved exposure

assessment. Research in mining environments, for example, demonstrates how real-time and aerial sampling methods can be applied to characterize toxic emissions from blasting and support mitigation strategies before contaminants disperse widely (Soubans, 2021). Such studies highlight the limitations of fixed-location or time-integrated sampling in environments where exposure conditions evolve rapidly.

Professional and conference literature similarly frames real-time monitoring as a bridge between environmental measurement and operational safety management. By providing immediate situational awareness, real-time systems support dynamic risk control and enhance coordination between workers, supervisors, and safety professionals (Brauch, 2015).

Organizational Integration and Health and Safety Management Systems

The successful adoption of DRIs depends not only on technological performance but also on organizational readiness and system integration. Research on health and safety management systems underscores the importance of leadership commitment, worker participation, communication, and continuous improvement during technology integration (Haas & Cauda, 2022). Without these elements, real-time data risks being underutilized or misinterpreted, potentially undermining trust and effectiveness.

From this perspective, DRIs are best understood as components of socio-technical systems in which measurement, human behavior, and organizational processes interact. Exposure science commentaries emphasize that measurement technologies must be embedded within governance structures that translate data into action and learning (Harper et al., 2015; Blount et al., 2015).

Training, Human Factors, and Data Interpretation

Human factors play a critical role in determining whether real-time exposure data lead to improved outcomes. Studies on training and engagement suggest that innovative approaches, including gamification-oriented tools, can enhance user understanding, situational awareness, and motivation in technology-rich work environments (Visci & De Robertis, 2022). Such approaches are particularly relevant when workers are expected to interpret and respond to real-time exposure information.

The literature therefore converges on the view that DRIs must be accompanied by structured training, clear communication strategies, and participatory implementation processes. These elements ensure that

real-time monitoring supports proactive exposure control rather than generating data overload or unintended behavioral consequences.

Collectively, the literature demonstrates that direct-reading instruments offer substantial potential to transform occupational exposure management. While technical capabilities and application strategies are well documented, fewer studies explicitly integrate DRIs into comprehensive, predictive exposure control frameworks that align with organizational systems and exposure science strategy. This gap underscores the need for conceptual models that connect real-time measurement, human decision-making, and proactive control—an issue addressed in the subsequent sections of this study.

Conceptual Framework and Methodological Approach

This study adopts a conceptual synthesis and systems-based methodological approach to examine how real-time direct-reading instruments (DRIs) can be repositioned from compliance-oriented monitoring tools to integral components of proactive occupational exposure control frameworks. Rather than relying on primary empirical data collection, the methodology integrates peer-reviewed literature, applied guidance documents, and exposure science theory to construct a coherent, practice-oriented framework consistent with contemporary occupational hygiene knowledge.

Conceptual Foundation

The conceptual framework is grounded in three complementary bodies of knowledge:

- Direct-reading instrumentation science, which defines the technical capabilities, limitations, and good-practice requirements for real-time aerosol and contaminant measurement (Vosburgh et al., 2022; Sheehan et al., 2022).
- Occupational exposure science, which emphasizes the role of exposure data in prevention, systems thinking, and strategic decision-making rather than isolated measurement (Harper et al., 2015; Blount et al., 2015).
- Health and safety management systems (HSMS), which provide the organizational structure through which new technologies are integrated while supporting worker well-being, participation, and continuous improvement (Haas & Cauda, 2022).

Within this foundation, DRIs are conceptualized not as standalone instruments but as dynamic data nodes embedded in a socio-technical system that links measurement, interpretation, decision-making, and control implementation.

Framework Structure: From Compliance to Prediction

The proposed framework organizes DRI use across three interrelated levels of exposure control:

- Operational level, where real-time measurements support immediate hazard recognition, task-based exposure characterization, and rapid corrective action.
- Tactical level, where aggregated DRI data are used to evaluate control effectiveness, identify exposure trends, and optimize work processes.
- Strategic level, where longitudinal exposure information informs risk forecasting, resource allocation, and organizational learning.

This layered structure reflects guidance on real-time monitoring for worker protection and compliance, while extending its application toward predictive risk management (Brauch, 2015; Siegel et al., 2019). Evidence from high-risk sectors, such as mining, further supports the value of real-time and aerial sampling data in anticipating hazardous emissions and guiding mitigation strategies before harmful exposures occur (Souban, 2021).

Methodological Approach

Methodologically, the study employs a qualitative integrative review and conceptual modeling approach. Key themes were identified across the cited literature, including instrument performance, data interpretation, organizational readiness, and human factors. These themes were systematically mapped to HSMS elements such as leadership commitment, training, communication, and continuous improvement to ensure that the proposed framework aligns with established safety management principles (Haas & Cauda, 2022).

Human-centered considerations, including training and user interaction with real-time data, are incorporated based on evidence that effective technology integration depends on comprehension and engagement rather than measurement alone. Gamification-oriented training tools and interactive learning approaches are highlighted

as mechanisms to enhance situational awareness and decision quality when working with complex real-time datasets (Visci & De Robertis, 2022).

Overall, this conceptual and methodological approach positions DRIs as enablers of anticipatory exposure control, consistent with the evolving role of exposure science in protecting worker health through prevention-focused, system-level interventions rather than retrospective compliance alone (Harper et al., 2015; Blount et al., 2015).

Results: Integrated Proactive Exposure Control Framework

The results of this study are presented in the form of an integrated, multi-layered framework that positions real-time direct-reading instruments (DRIs) as central components of proactive occupational exposure control systems. Rather than functioning solely as compliance tools, DRIs are shown to enable continuous feedback, anticipatory decision-making, and organizational learning when embedded within structured management and training systems. The framework synthesizes evidence from aerosol instrumentation research, real-time monitoring practice, exposure science strategy, and safety management systems.

Structural Architecture of the Proactive Exposure Control Framework

The proposed framework is organized into three interdependent layers operational, tactical, and strategic each supported by real-time exposure data streams. At the operational level, DRIs provide immediate detection of exposure variability at the task and worker interface, enabling rapid corrective action. This aligns with documented applications of aerosol DRIs for task-based assessment and source identification (Sheehan et al., 2022). At the tactical level, aggregated real-time data are used to evaluate control effectiveness and process stability, consistent with good practice guidance for instrument deployment and interpretation (Vosburgh et al., 2022). At the strategic level, longitudinal exposure

Table 1: Comparison of Traditional Compliance Monitoring and Proactive DRI-Based Exposure Control

<i>Dimension</i>	<i>Traditional compliance monitoring</i>	<i>Proactive DRI-based exposure control</i>
Primary Objective	Demonstrate compliance with exposure limits	Anticipate and prevent hazardous exposures
Sampling Strategy	Periodic, integrated sampling	Continuous or near real-time monitoring
Data Resolution	Time-weighted averages	Task-, event-, and process-specific
Feedback Speed	Delayed (post-analysis)	Immediate or near-immediate
Role in Decision-Making	Retrospective documentation	Predictive and adaptive control
Worker Engagement	Limited involvement	Active participation and feedback

Table 2: Comparison of Traditional Compliance Monitoring and Proactive DRI-Based Exposure Control

<i>Dimension</i>	<i>Traditional compliance monitoring</i>	<i>Proactive DRI-based exposure control</i>
Sampling approach	Periodic, integrated sampling	Continuous or near real-time sensing
Data resolution	Time-weighted averages	Task-, event-, and process-based
Primary purpose	Regulatory compliance	Hazard anticipation and prevention
Feedback latency	Delayed (days to weeks)	Immediate to near-immediate
Decision orientation	Retrospective	Predictive and adaptive

datasets support trend analysis, predictive modeling, and continuous improvement, reflecting the broader vision of exposure science as a decision-support discipline (Harper et al., 2015; Blount et al., 2015).

Real-Time Data Flow and Control Feedback Mechanisms

Results indicate that the effectiveness of DRIs depends on their integration into closed-loop control systems rather than isolated measurement. Real-time data flows from sensors to workers, supervisors, and management dashboards, enabling tiered responses proportional to exposure severity. Practical guidance emphasizes that alarm thresholds, contextual interpretation, and communication protocols are critical to prevent misuse or alarm fatigue (Siegel et al., 2019; Brauch, 2015).

Evidence from high-risk industrial environments, including mining, demonstrates that real-time and spatially resolved monitoring can support early detection of hazardous emissions and timely mitigation (Soubans, 2021). These findings reinforce the value of DRIs as dynamic inputs to exposure control, rather than static indicators of limit exceedance.

Functional Roles of Direct-Reading Instruments Across Framework Layers

The analysis identifies distinct but interconnected functional roles for DRIs across organizational levels. At the operational layer, instruments serve as immediate hazard indicators. At the tactical layer, they support evaluation of engineering and administrative controls. At the strategic layer, they contribute to exposure intelligence, enabling scenario analysis and forward-looking risk management consistent with exposure science strategy frameworks (Harper et al., 2015).

Human Factors, Training, and System Reliability

Results further demonstrate that technological capability alone is insufficient for proactive exposure control. Integration must account for human factors, training, and organizational readiness. Health and safety management system elements such as leadership commitment, worker participation, and continuous improvement are critical

enablers of successful technology integration (Haas & Cauda, 2022). Without adequate training, real-time data may be misinterpreted or ignored, undermining potential benefits.

Innovative training approaches, including gamification-oriented tools, show promise in improving user engagement and situational awareness in data-rich environments (Visci & De Robertis, 2022). These approaches support consistent interpretation of DRI outputs and reinforce appropriate behavioral responses to exposure signals.

Synthesis of Results

Collectively, the results demonstrate that integrating DRIs into proactive occupational exposure control frameworks transforms exposure management from a retrospective compliance exercise into a predictive, prevention-oriented system. When aligned with good instrumentation practices (Vosburgh et al., 2022), application-driven deployment (Sheehan et al., 2022), robust management systems (Haas & Cauda, 2022), and exposure science principles (Harper et al., 2015; Blount et al., 2015), real-time monitoring enables earlier intervention, improved control effectiveness, and sustained protection of worker health.

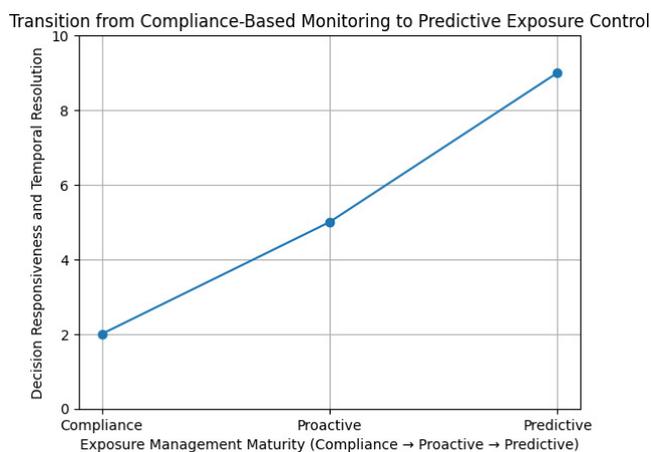


Fig 1: Line graph shows the upward transition from Compliance → Proactive → Predictive, illustrating increased decision responsiveness and temporal resolution.

Table 3: Functional Roles of Direct-Reading Instruments within the Integrated Framework

Framework layer	Role of DRIs	Primary outputs
Operational	Immediate exposure detection	Alarms, instantaneous concentrations
Tactical	Control and process evaluation	Trends, control effectiveness metrics
Strategic	Organizational learning and prediction	Exposure profiles, leading indicators

Table 4: Enablers and Barriers to Effective Integration of Direct-Reading Instruments

Category	Key enablers	Common barriers
Technical	Calibration protocols, validation	Sensor drift, environmental interference
Organizational	Leadership support, clear governance	Resistance to change
Human factors	Training, intuitive interfaces	Data overload, misinterpretation

DISCUSSION AND IMPLICATIONS

The analysis presented in this study highlights a fundamental shift in occupational exposure management from retrospective compliance verification toward predictive and prevention-oriented control. The integration of real-time direct-reading instruments (DRIs) into exposure control frameworks enables this transition by providing temporally rich data that capture variability, task-specific emissions, and transient peak exposures

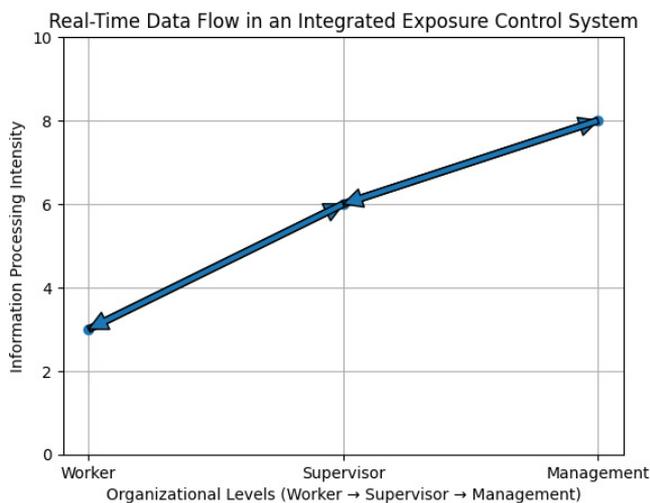


Fig 2: The Systems flow graphs show organizational levels (Worker → Supervisor → Management) with bidirectional arrows representing feedback loops and real-time data exchange.

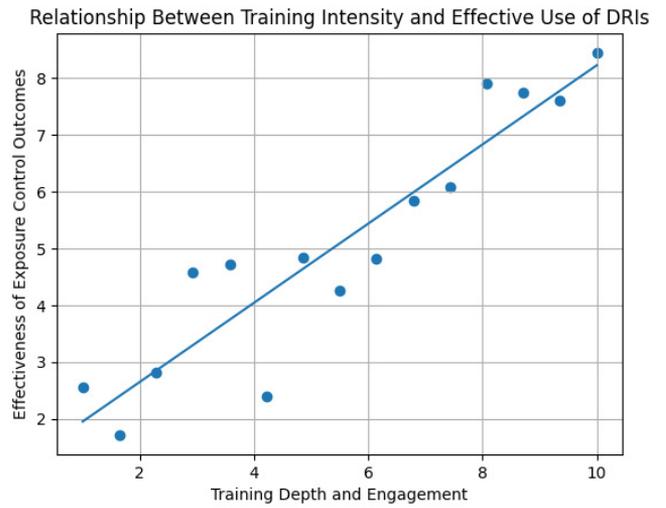


Fig 3: The Scatter plot with trend line demonstrates the positive correlation between training intensity and effective exposure control outcomes.

that are often obscured by traditional time-integrated sampling methods. Consistent with recent reviews, the value of DRIs lies not only in their measurement capabilities but in how their outputs are contextualized, interpreted, and acted upon within occupational health systems (Vosburgh et al., 2022; Sheehan et al., 2022).

Interpretation of Findings in Relation to Existing Literature

The proposed framework reinforces the view that DRIs are most effective when deployed as part of a systems-based exposure management strategy rather than as standalone compliance tools. Applications literature demonstrates that real-time aerosol monitoring supports source identification, evaluation of engineering controls, and immediate corrective actions during work tasks (Sheehan et al., 2022). However, without structured integration into decision-making processes, such data risks being underutilized or misinterpreted. This concern aligns with earlier guidance emphasizing the importance of alarm strategies, data validation, and user competency in real-time detection systems (Siegel et al., 2019; Brauch, 2015).

From an exposure science perspective, the findings are consistent with broader disciplinary calls for a more strategic use of exposure data in protecting worker health. Commentaries on the future role of exposure science emphasize moving beyond measurement for documentation toward anticipatory and intervention-focused applications (Harper et al., 2015; Blount et al., 2015). The framework developed in this study operationalizes these principles by explicitly linking real-time measurements to operational, tactical, and strategic levels of control.

Organizational and Management Implications

The results underscore that successful DRI integration is as much an organizational challenge as a technical one. Embedding real-time monitoring into health and safety management systems requires alignment with core system elements, including leadership commitment, worker participation, communication, and continuous improvement. Evidence suggests that technology integration initiatives that neglect these elements may inadvertently increase cognitive load or erode trust among workers (Haas & Cauda, 2022). In contrast, when DRIs are introduced within a supportive management system, real-time data can enhance worker well-being by increasing transparency and enabling timely risk reduction.

High-risk industries provide illustrative examples of these dynamics. Research on toxic emissions from blasting activities demonstrates how real-time and aerial sampling approaches can inform immediate mitigation strategies and long-term process redesign when integrated into operational planning (Soubans, 2021). These findings reinforce the need for governance structures that clearly define data ownership, response protocols, and accountability mechanisms.

Human Factors, Training, and Data Interpretation

Another critical implication concerns human factors and training. The effectiveness of predictive exposure control depends on the ability of workers and supervisors to correctly interpret real-time data and translate it into appropriate actions. Emerging training approaches, including gamification-oriented tools, show promise in enhancing engagement, situational awareness, and learning outcomes in technology-rich environments (Visci & De Robertis, 2022). Such approaches are particularly relevant for DRIs, where misinterpretation of short-term fluctuations or sensor limitations could lead to inappropriate responses.

This reinforces earlier guidance that emphasizes good practice in instrument selection, calibration, and contextual interpretation as foundational requirements for meaningful use of DRIs (Vosburgh et al., 2022). Training should therefore be viewed not as a supplementary activity but as a core component of proactive exposure control frameworks.

Implications for Policy and Practice

At the policy and practice level, the findings suggest that regulatory and organizational focus should evolve from exclusive reliance on compliance metrics toward encouraging predictive and preventive use of exposure data. While occupational exposure limits remain

essential benchmarks, real-time monitoring enables organizations to act before limits are exceeded, thereby reducing cumulative risk. Practical guidance on real-time detection systems already supports this direction by framing such technologies as tools for both compliance and worker protection (Siegel et al., 2019).

For practitioners, the framework offers a structured approach to integrating DRIs into existing programs, emphasizing that technological adoption should be accompanied by clear objectives, defined response strategies, and continuous evaluation. For researchers, the study highlights the need for further empirical work examining how real-time exposure data can be translated into predictive indicators and decision-support tools across diverse occupational settings.

Broader Implications for Exposure Science

More broadly, the findings contribute to the ongoing evolution of exposure science as a proactive discipline. By positioning DRIs within a predictive control paradigm, the framework supports the strategic vision articulated in foundational exposure science literature, which calls for integrating measurement, modeling, and intervention to better protect human health (Harper et al., 2015; Blount et al., 2015). The shift from compliance to prediction is therefore not merely technological but conceptual, reflecting a maturation of occupational exposure control toward more adaptive and resilient systems.

CONCLUSION

This study demonstrates that the integration of real-time direct-reading instruments represents a substantive evolution in occupational exposure control, shifting practice from retrospective compliance verification toward proactive and predictive risk management. The evidence synthesized across the literature indicates that direct-reading instruments, when properly selected, calibrated, and interpreted, provide exposure information at a temporal and spatial resolution that fundamentally changes how hazards can be identified, understood, and controlled (Vosburgh et al., 2022; Sheehan et al., 2022). Rather than serving solely as rapid compliance tools, these instruments enable dynamic assessment of work tasks, processes, and controls, supporting earlier intervention and more effective prevention.

The results also emphasize that technological capability is not enough to make any significant changes to worker protection. To implement real-time monitoring successfully requires its integration with the established health and safety management systems with the focus on the leadership commitment, worker participation, communication, and continuous improvement (Haas

and Cauda, 2022). In the absence of such integration, there is a risk of underutilization of real time data, misunderstanding of real time data or even the real time data are taken to mean surveillance instead of protection. Recommendations on real-time detection systems note that it is critical to have strong governance, alarm plans, and decision-making procedures that will see data translate into prompt and suitable control measures (Siegel et al., 2019; Brauch, 2015).

Specific research on sectors is also an additional indication of the preventive capacity of real-time and near-real-time exposure measures. Mining and other high-risk industries research indicates that more complex sampling and monitoring methods can detect dangerous emissions at an early stage of their formation, and mitigate them before many people become exposed to them (Soubans, 2021). Simultaneously, new methods of training and interaction, such as the gamification-based solution, show how employee knowledge and willingness to accept monitoring technologies can be reinforced to enhance the efficiency of the exposure management strategies in practice (Visci and De Robertis, 2022).

Exposure science-wise, the shift towards real-time, predictive models has been in line with the disciplinary wide-ranging cries of exposure data providing information on prevention, system learning, and strategic decisions instead of being a compliance reporting endpoint (Harper et al., 2015; Blount et al., 2015). The integration of direct-reading instruments in the closed-loop control systems enables organizations to integrate exposure measurements with engineering, administrative, and behavioral controls, which supports a prevention based hierarchy of controls.

To sum up, introduction of real-time direct-reading tools into proactive occupational exposure management systems presents an opportunity towards more adaptive, resilient and efficient worker protection. By being coupled with proper measurement practices, strong management structures, and people-friendly implementation plans, real-time monitoring can make exposure management a proactive ability instead of a reactive duty that can help to achieve long-term outcomes of occupational health and safety.

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