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COMMENTARY

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Advanced sensor technologies and the future of work

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Abstract

Exposure science is fundamental to the field of occupational safety and health. The measurement of worker exposures to hazardous agents informs effective workplace risk mitigation strategies. The modern era of occupational exposure measurement began with the invention of the personal sampling device, which is still widely used today in the practice of occupational hygiene. Newer direct-reading sensor devices are incorporating recent advances in transducers, nanomaterials, electronics miniaturization, portability, batteries with high-power density, wireless communication, energy-efficient microprocessing, and display technology to usher in a new era in exposure science. Commercial applications of new sensor technologies have led to a variety of health and lifestyle management devices for everyday life. These applications are also being investigated as tools to measure occupational and environmental exposures. As the next-generation placeable, wearable, and implantable sensor technologies move from the research laboratory to the workplace, their role in the future of work will be of increasing importance to employers, workers, and occupational safety and health researchers and practitioners. This commentary discusses some of the benefits and challenges of placeable, wearable, and implantable sensor technologies in the future of work.

KEYWORDS

e-textiles, implantables, placeables, sensors, wearables

1 | INTRODUCTION

Exposure science is fundamental to the field of occupational safety and health. The measurement of worker exposures to hazardous agents informs effective workplace risk mitigation strategies.[1] Beginning in the mid-1930s, occupational exposure science was based on a two-step strategy—collecting air samples from the work environment followed by laboratory analysis using standardized methods.[1–3] In 1960, the personal sampler was invented, and it demonstrated that area sampling can underestimate worker exposures.[4,5] Since then, personal sampling has become accepted practice in occupational hygiene.[1]

While advancing the accuracy of occupational exposure science, personal sampling is still dependent on subsequent laboratory analysis for actionable results.[6] Slow turnaround between sample collection and laboratory analysis can stymie implementation of timely workplace risk mitigation strategies. Recognition of the need to detect hazardous exposures in time to rapidly mitigate harmful effects has led to the research and development of "direct-reading" devices that can sense the presence of a toxic agent, collect a sample, analyze the sample on an intermittent or continuous basis, and even display the analytical results in "real-time," or at the end of a shift, to the individual who can then mitigate the exposure.[6,7]

Among early direct-reading devices were the pocket radiation dosimeter patented in 1935[8] and the noise dosimeter first patented in the 1950s and miniaturized in the 1970s.[9] These early direct-reading sensors have since been joined by a number of field-portable, real-time sensor devices like gas and vapor monitors[10]; real-time aerosol monitors[11]; X-ray fluorescence detectors for metals[12]; and immunochemical assay kits for methamphetamines, microorganisms, and other kinds of immunologically active contaminants.[6]

Newer direct-reading sensor devices are incorporating recent advances in electrochemical, optical or mechanical transducers, nanomaterials, electronics miniaturization, portability, batteries with high-power density, wireless communication, energy-efficient microprocessing, and display technology.[13–16] Commercial applications of new sensor technologies have led to a variety of health and lifestyle management devices for everyday life. These digital health technology tools like fitness trackers, smartwatches, and smartphones function as real-time monitors of various physiological and disease-related signals.[17,18] These technologies have led to advances in connected health[19,20]; telemedicine[21,22]; sports analytics[13,23]; ambient intelligence[24]; and workplace "physiolytics."[25,26]

As advanced sensor technologies are commercialized for consumer use, they are also being investigated as new occupational and environmental exposure science tools.[27–30] As next-generation exposure assessment tools, a new generation of sensor technologies can be outward or inward looking.[31] Detecting harmful chemical, physical, or biologic agents in the work environment to which a worker may be exposed are examples of sensors that look outward *from* the worker, that is, environmental sensors.[31] Detecting a worker's location, movement or proximity to a hazard, physical location sensors, or sensing a worker's physiological state, are examples of sensors that look inward *to* the worker to assess the effects exposure to hazardous agents may cause, that is, biosensors.[31]

Recognizing a role in the present and in the future of work for these types of sensor technologies to assess worker exposures, the National Institute for Occupational Safety and Health (NIOSH) established a *Center of Excellence for Direct Reading Sensor Technologies* in 2014. The Center conducts and coordinates basic and applied research, develops evidence-based recommendations, and engages the occupational safety and health community in the new field of emerging direct-reading sensor technologies for the workplace.[32]

Newer sensor technologies have the potential to greatly accelerate advances in occupational exposure science. Innovative strategies using commercialized consumer sensor technologies are being investigated and introduced into the workplace. As next-generation placeable, wearable and implantable sensor technologies move from the research laboratory to the commercial market, and are then introduced into the workplace, their role in the future of work will be of increasing importance to employers, workers, and occupational safety and health researchers and practitioners. This commentary discusses the benefits and challenges of some placeable, wearable and implantable sensor technologies in the future of work.

2 | SENSOR TAXONOMY

Existing and newer sensor technologies can be categorized into three broad categories—placeable, wearable, and implantable devices. Placeable sensor devices can be placed in and around the workplace to collect information from the ambient work environment (*placeables*). The vast majority of wearable sensors in current use can be attached to a worker's clothing, head, arms or wrists, upper/lower body, or feet,[15] worn as computer-display eyeglasses,[33] or contact lenses,[34] or placed in the ear canal[35] (*attached or portable wearables*). Two other types of attached wearables are beginning to move along the research to workplace application pathway. These are sensors that are woven into textiles that can be worn by a worker as clothing[36] (*electronic textile wearables*) and sensors incorporated in thin "skin-like" films or tattoos that can be applied directly to the epidermis[37–39] (*electronic epidermal wearables*). The third variety of new sensors are implantable sensors that can be inserted into the skin via microneedles,[14,40] microchips,[41] or can be ingestible[42,43] (*implantables*).

3 | PLACEABLE SENSORS

Placeable sensors are the most commercially developed for use in the workplace and have a long history. For several years, sensors have been placed around a workplace to detect worker occupancy, movement within the workplace, and a variety of atmospheric factors.[15] New opportunities and applications for placeable sensors involve networks of multiple sensor nodes distributed around a workplace that can measure the same or several different hazards. As a new occupational exposure assessment strategy, wireless area sensor networks can overcome the low sample size limitations of personal sampling by monitoring multiple analytes in real-time,[44] be more cost-effective than personal sampling methods,[45] and can characterize the distribution of hazards with a high degree of spatiotemporal resolution.[44,46] The challenge facing wireless placeable sensor networks continuously collecting information from many micro-sensor nodes is how to efficiently process the information coming from each node into timely, actionable information.[47,48] The newest application of wireless *area* sensor networks is the wireless *body* sensor network using wearable instead of placeable sensors.[49]

4 | WEARABLE SENSORS

4.1 | Attached wearable sensors

Sensors are a part of a larger world of industrial wearable technologies that hold promise as new tools to enhance safety and health at work.[50] Of the types of wearable sensors, sensors that can be attached or linked to the worker are the most prevalent in work settings today. Designed with "wear-and-forget" functionality,[36,51] attached wearables can be worn on or over clothing such as vests[52]; attached to safety helmets[53,54]; incorporated into footwear[55]; worn as smart eyeglasses[33] or contact lenses[34]; or placed in the external auditory canal.[35] Optimizing the location of attached wearables depends on the sensor's monitoring purpose, need for interaction between the sensor controls and the worker, display reachability, weight, and worker acceptance.[51]

Wearable sensor technologies are not without risk. Among the physical hazards presented by wearable technologies are the following: (1) dermal irritation if exposure to the chemicals contained in device occurs; (2) chemical burns if a battery leaks a reactive material; (3) thermal burns if a wearable battery suddenly discharges its stored energy; or (4) auditory damage if an implanted audio device malfunctions or "plays" a signal from another source.[56] A fire hazard may occur if the electrical equipment embedded in wearable technologies becomes a source of ignition in a hazardous location, for example, a Class I explosive environment.[57] In addition to risks inherent to sensors, several barriers to adoption of sensor technologies have been identified among safety professionals—sensor durability, good manufacturing practices, the cost-benefit ratio for implementation, concerns about worker acceptance, and employer and worker conformance with a sensor's intended use.[58]

4.2 | Construction

Applications of attached wearable sensing technologies have the potential to reduce injuries and illnesses arising from the most prevalent hazards found in the construction industry.[59] For example, proximity detection and location tracking can prevent caught-by, struck-by, electrocution, and confined space incidents.[59] Environmental sensing of ambient conditions and workers' physiological responses can prevent exposure to fire, explosions, vibration, heat, cold, toxic gases, and other chemical and physical stressors.[60]

Existing research into the role of wearable sensing technologies in construction have focused on how sensors can aid in detecting and monitoring the risk factors that lead to work-related musculoskeletal disorders (WMSDs), falls from elevations, and physical fatigue.[60] Attached wearable sensors with capabilities to monitor a worker's physical loads and kinematic parameters can reduce the risk of awkward postures and excessive physical loads leading to WMSDs from manual materials handling tasks.[61,62] Proximity sensors[63] and fall detection sensors to alert emergency response that a fall has occurred[64] have been used to augment standard fall protection measures like safety harnesses. Models using minimally intrusive sensors for detecting and monitoring whole-body fatigue in physically demanding occupations have shown promise in initial research studies.[65,66] In addition to specific sensor applications, the construction worksite is also being envisioned as an "sensored" workplace where tools, equipment, and personnel are linked together in a multi-sensor network to augment overall construction site safety management.[63,67]

4.3 | Confined spaces

Attached wearable sensor technologies can optimize work in dangerous environments like confined spaces where asphyxiation from inert or toxic gases, fire or explosion can occur while a worker is within an Occupational Safety and Health Administration (OSHA) permit-required confined space.[68] To protect confined space workers, a suite of wearable sensors is needed.

A confined space monitoring system was developed and utilized for monitoring workers in OSHA-defined confined spaces during an aircraft maintenance case study[69] The goal of the case study was to improve both work efficiency and worker safety by addressing challenges associated with existing remote worker monitoring systems. These challenges are as follows: (1) determining if a worker is incapacitated; (2) locating a worker inside an aircraft's confined space; (3) sampling atmospheric composition; and (4) monitoring worker activity by means of a streamlined data acquisition system.[69] The confined space monitoring system was composed of commercial wearable sensors, algorithms operating in a central expert system, and a customized interface design focused on the augmentation of operator decision making.[69] In this case study, a single controller monitored various sensors that reported workers' respiration and heart rates, workers' location, and environmental gas conditions. The objective was to identify and respond to emergency situations more quickly than in traditional approaches where an attendant outside of the confined space communicates verbally with the confined space worker. While implementation of this confined space monitoring system led to increases in productivity and worker perception of safety, the case study authors acknowledge that the proposed system would not be able to prevent incidents such as entrapment or blunt force trauma.[69]

While these types of sensor implementation case studies show promise, the challenges associated with monitoring and transmission of physiological, location, and atmospheric gas measurement data remain to be overcome.[70] Once proved operational, these wearable sensor technologies can greatly enhance the safety profile of many dangerous environments into which workers must enter.

4.4 | Mining

Existing commercial wearable sensors are being adapted for use in the above ground and underground mining environment. Enhancing situational awareness in the mining environment where miners and machines work in proximity to each other can be aided by wearable proximity sensors mounted on a safety helmet and connected by wireless networks.[71] Utilization of a combination of a safety vest and a smart helmet equipped with location and proximity sensors, air contaminant sensors for mine dusts, methane and carbon monoxide, smart eyewear, and a smart watch can serves an integrated wearable exposure assessment and management system to enhance mine safety.[72] A wearable dust assessment sensor developed by NIOSH in consultation with labor and industry provides direct reading, real-time information about the level of respirable coal dust exposure near the coal miner. The continuous personal dust monitor (CPDM) can empower miners to take corrective action like increasing ventilation or repositioning to locations with less dust when the CPDM displays hazardous levels.[73]

4.5 | Advanced manufacturing

Human workers are now sharing the same workspace with robotic devices. These robots can be considered an extension of the worker and can also function as extremely sophisticated sensing systems. These new emerging robotic systems are known as collaborative robots or "cobots." One type of cobot, the collaborative mobile manipulator, operates alongside human workers in some advanced manufacturing settings.[74] The safe operation of a mobile manipulator depends on "communication" between the human worker and the cobot. Wearable sensors attached to the human worker that track body location and movement and visual fields can be a means to ensure the safety of human-cobot interaction.[75]

4.6 | Electronic textile wearables

Wearable textile sensors represent a convergence of material science and electronics which makes possible the embedding of electronic circuitry within textiles to create a new class of textiles called smart textiles, intelligent textiles, or electronic or e-textiles.[76,77] Smart function can be integrated into fabric to produce an e-textile in three ways. The invention of the conductive polymer in 1977 made possible integration of functionalized yarns (metallic wires or metalized textile yarns) into textile architecture.[78] Second, traditional weaving and knitting fabrication processes can be used and result in an e-textile fabric that is lighter weight, denser integration of electronic and optional functionalities, and more deformation resistant.[76] Third, smart capabilities can be added post-fabrication through embroidery, printing, gluing, or lamination.[79]

The types of embedded sensors integrated into e-textiles can include those sensing changes in the ambient environment, like clothing integrated with gas sensors[80] or those measuring human internal chemical parameters.[81] Electrochemical sensors integrated into e-textiles made from conductive polymers that exhibit both the mechanical properties of polymers and the electrical conductivity of semiconductors have potential application not only in medicine and sports, but also in occupational safety and health.[36] Electrochemical sensors in e-textiles can be used to sample human perspiration non-invasively and on a continuous basis.[36]

Research-to-date indicates that textile chemical sensors can be used to sample for pH (measure of acid/base balance), various electrolyte ions such as sodium (Na^+), potassium (K^+), chloride (Cl^-) and ammonium (NH_4^+), glucose and lactate, as biomarkers of health.[36] Active or reactive textiles may not only have sensing capabilities, but they may also be engineered to provide therapeutic interventions for the wearer. Examples of such interventions include mechanical pressure, heating, cooling, or electrical stimuli.[82]

While e-textiles are a promising type of wearable sensor technology, there are many technical challenges to their commercial or workplace application. These challenges include analytical requirements, power supply, data acquisition and processing, communication, and maintaining the functionality of epidermal materials during use in relevant environments.[83] Despite these challenges, e-textiles may soon play a role in the future of work.[84]

4.7 | Electronic epidermal wearables

Interest in devices that can sample physiological processes directly through contact with the epidermis date from the birth of encephalography in 1929.[85] In the last decade, a new class of sensor technology—epidermal electronic systems—are being investigated to measure electrophysiological activity produced by the heart, brain, and skeletal muscles.[39] Ultra-thin, "skin-like" membranes, with tattoo-like conformability and stretchability without actual transdermal ink injection, provide the structural foundation for sensor electrodes, power supply, and communication components that can non-invasively collect physiological information from within the body through the epidermis.[86] A whole class of tattoo-based wearable electrochemical devices are broadening the concept of epidermal chemical sensing.[37] Epidermal wearable sensors are now being investigated to measure pH, various electrolytes, and other metabolites on or under the skin physically, chemically, or electrochemically as point-of-care applications.[87]

Going deeper into the skin via microneedles, transdermal skin sensors were first used commercially for drug and vaccine delivery.[40] The most widely used transdermal sensor technology in use today is the continuous transdermal glucose monitor.[88] Leveraging more than three decades of advances in enzyme electrodes found in simple and ultra-low-cost finger-prick glucose test strips, commercialization of the continuous glucose monitoring is the model for all epidermal and transdermal wearable sensors, that is, to measure the continuous status of an important internal biomarker.[89] Advances in transdermal microneedles expand the scope of electronic epidermal wearables. Gaining access below the epidermis, transdermal devices can sample the interstitial fluid space.[38,90] Although primarily a subject of current clinical research interest, electronic epidermal and transdermal wearables may have a role in detecting biomarkers of occupational exposure and disease in the future of work.

Electronic epidermal wearables are advanced enough to facilitate physiologic monitoring of heart rate, respiration, core body temperature, body water loss, and estimation of thermal load to identify developing heat stress. Workers exposed to hot environments who are engaged in strenuous physical activities such as agriculture, construction, mining, and firefighting work can be at higher risk of heat stress. These and other types of workers may benefit from the advantages electronic epidermal wearables have to offer.

5 | IMPLANTABLE SENSORS

Wearable sensors—attached, electronic textiles or epidermal—are promising new exposure science tools, but the distance between a target physiological process being monitored and the sensor device can weaken signal transmission. Sensors implanted closer to the monitoring target within the human body can provide more accurate measurements.[91] Implantable devices like cardiac pacemakers and defibrillators have been in medical use since the 1960s and can both sense and act on physiological signals occurring within the body.[43]

Newer implantable wireless sensor technologies include transdermal microneedles for glucose monitoring[14]; orthopedic prosthetics to measure strain and force data[91,92]; and microchips to monitor tissue oxygen levels.[93] When technical challenges can be addressed related to sensor power supply and wireless communication capabilities, together with regulatory requirements of the US Food and Drug Administration for medical devices implanted in the human body,[94] the ability of implantables to detect and quantify a wide range of physiological events within the body in real-time may have further application in clinical diagnosis and in the future of work.

The ingestible sensor has the greatest likelihood of moving from research into clinical and workplace applications. For example, as a clinical tool, an ingestible sensor can gather images of the gut lumen, sample enzymes, metabolites, hormones, and the microbiome.[42] As an occupational tool, an ingestible sensor can monitor core temperature for workers at risk of heat stress. Agricultural workers,[95] exercise enthusiasts,[96] athletes,[97] astronauts,[98,99] deep underground miners,[100] and others at risk of hazardous thermal stress could benefit from continuous core body temperature monitoring by means of a wireless ingestible sensor.[101] As with other advanced sensor technologies, ingestible sensors have limitations. Ingestible thermometers for measurements of core temperature would have to be ingested several hours before use and can function only until the device passes out of the lower gastrointestinal tract.[102] Ingesting sensors to determine intestinal temperature could be considered by workers as an invasive medical procedure, raising ethical and legal issues.

6 | NEWER SENSORS AND THE WORKER

As an exposure science tool, newer sensors exhibit an increased level of intrusiveness for workers that increases along a continuum from placeable sensors, through attached wearables like e-textiles, epidermal, and transdermal wearables, to implantable sensors. Worker acceptance is a critical factor in adoption of advanced sensors in the future of work. Placeables, wearables, and implantables may enhance organization performance, workplace safety, and the health and well-being of workers, but they may also be viewed as a form of coercive employer surveillance.[103]

Wearable sensors present a set of common concerns to workers. The quality, comfort, and ease of use of sensor technologies are important acceptance factors for workers engaged in physically demanding work.[104] The perceived performance of a sensor to increase safety in the workplace is a strong predictor of worker acceptance.[105] Sensors that can detect workers' proximity to workplace hazards like energized electrical hazards, toxic gases, and fire/smoke are viewed as critical safety functions having mutual value to both workers and management.[106]

Workplace acceptance is also linked to concerns about the use of data collected by wearable sensors by the employer, but sometimes for unexpected reasons. In a recent survey, construction workers rated environmental sensor functions as having greater impact on worker safety and health than wearable sensors sampling physiological outputs but were more open to sharing physiological data than environmental data.[106] This was so because physiological sensors do not track a worker's location as environmental sensors do.[106]

In another large study of construction workers, workers were found to accept utilizing the data collected from a wearable sensor if that data could identify a worker's personal health risks or promote a fellow worker's occupational safety.[107] Even though some construction worker surveys have shown that workers are not open to sharing data derived from sensors,[108] a more recent survey shows that a majority of workers surveyed—especially those who have more experience with wearable sensors—are willing to share output data with their employer.[106]

Wearable sensor technologies like other devices in the larger world of Internet-of-Things (IoT) devices pose security and privacy challenges that will require new cybersecurity solutions. Sensors can now sense data with more accuracy, process it by themselves, and send it to the neighboring node within a network or send it to a central hub. However, robust and reliable cybersecurity mechanisms are not yet been fully developed for these sensors due to their limited energy and computation power.[109] Encrypted security solutions need to be explored to lessen the security risks associated with unsecured data transmission for the entire class of new sensor technologies.[110]

Acceptance of environmental and physiological sensors by workers depends on how well employers and occupational safety and health professionals partner with workers to introduce fully transparent sensor-technology-based programs.[111] To ensure successful adoption of sensor technologies in the workplace of the future, best practice recommendations include: (1) making participation in sensor monitoring voluntary and not coercive; (2) ensuring all sensor data that are used is transparent to the worker; (3) utilizing only sensors that have been validated by interventional effectiveness studies before being applied in the workplace; and (4) ensuring that data collection is limited to working hours.[112] Importantly, all data outputs should conform to the latest secured data transmission governance and stored under robust cybersecurity protections.[113]

7 | REGULATORY FRAMEWORK

Detection and measurement of an occupational chemical or physical agent is an essential component of mandatory safety and health standards promulgated by OSHA and the Mine Safety and Health Administration (MSHA). To reduce the risks to worker safety and health, the OSHA and MSHA regulatory framework relies on a safe limit of exposure to workers as measured by area and personal breathing zone sampling devices. For example, the OSHA Noise Exposure Standard sets a legally permissible exposure limit for noise as an 8-h time-weighted average sound level (TWA) of 85 decibels measured on the A scale of a standard sound level meter at slow response.[114] As noise sensing devices become more sophisticated, portable, and capable of real-time measurement, they can be mandated in a regulatory framework. For example, the CPDM has been incorporated in MSHA's 2014 final rule aimed at controlling respirable coal dust exposure in mines.[115] The inclusion of the CPDM by MSHA in its coal dust standard is a sign of the maturity of real-time sensors from a regulatory framework perspective. Advanced sensors may play an increasing role in 21st century exposure science and in the occupational safety and health regulatory framework.

8 | CONCLUSION

New placeable, wearable, and implantable sensor technologies represent advances in the field of occupational exposure science. As these sensor technologies move from the research laboratory into the workplace, we need to be aware of both the benefits and challenges they present for workers, employers, and safety and health practitioners. Sensors may make exposure assessment more convenient and comprehensive, but the intrusiveness that accompanies ubiquitous worker monitoring needs to be balanced by a respect for privacy, trust that personal health data remains secure, and a collaborative agreement between *sensored* workers and their employers that any advanced sensor technology introduced into the workplace directly benefits worker safety and health.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

DISCLOSURE BY AJIM EDITOR OF RECORD

John Meyer declares that he has no conflict of interest in the review and publication decision regarding this article.

AUTHOR CONTRIBUTIONS

All authors conceived and drafted the work, revised it critically for important intellectual content; gave final approval of the version to be published; and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

DATA AVAILABILITY STATEMENT

Data derived from public domain resources. The data that support the findings of this study are available online through Google Search. See references [1-115] for Internet access to the source material.

DISCLAIMER

The findings and contributions of the authors in this report do not necessarily represent the views of the National Institute for Occupational Safety and Health, the Centers for Disease Control and Prevention, or the US Department of Health and Human Services.

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REFERENCES

1. Fenske RA. For good measure: origins and prospects of exposure science (2007 Wesolowksi Award Lecture). *J Expo Sci Env Epid*. 2010;20:493-502. doi:10.1038/jes.2010.26
2. Cherrie JW. The beginning of the science underpinning occupational hygiene. *Ann Occup Hyg*. 2003;47(3):179-185. doi:10.1093/ANNHYG/MEG030
3. Harper M, Weis C, Pleil JD, et al. Commentary on the contributions and future role of occupational exposure science in a vision and strategy for the discipline of exposure science. *J Expo Sci Environ Epidemiol*. 2015;25(4):381-387. doi:10.1038/jes.2014.91
4. Sherwood RJ, Greenhalgh DMS. A personal air sampler. *Ann Occup Hyg*. 1960;2:127-132.
5. Sherwood RJ. On the interpretation of air sampling for radioactive particles. *Am Ind Hyg Assoc J*. 1966;27(2):98-109. doi:10.1080/00028896609342800
6. Pearce T, Coffey C. Analytical performance issues: integrating direct-reading exposure assessment methods into industrial hygiene practice. *J Occup Environ Hyg*. 2011;8(5):D31-D36. doi:10.1080/15459624.2011.569314
7. Cauda E & Hoover M Right Sensors Used Right: A Life-Cycle Approach for Real-Time Monitors and Direct Reading Methodologies and Data. Washington, DC: National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, US Dept of Health and Human Services; 2019. Accessed September 27, 2021. https://blogs.cdc.gov/niosh-science-blog/2019/05/16/right-sensors-used-right/. Accessed October 11, 2021.
8. Lauritsen CC, inventor; California Institute of Technology, assignee. Roentgen Meter. US patent 2,022,117. November 26, 1935. Accessed September 27, 2021. https://patentimages.storage.googleapis.com/90/fb/2e/89e3ee4925f234/US2022117.pdf
9. Steger JO; inventor; Ball Corporation, assignee. Audio Dosimeter. US Patent Office. 3,884,086. July 23, 1973. Accessed September 27, 2021. https://patentimages.storage.googleapis.com/75/89/13/ab6773a988738e/US3884086.pdf
10. National Institute for Occupational Safety and Health. Components for evaluation of direct-reading monitors for gases and vapors. A NIOSH Technical Report, Publication No. 2012–162. Washington, DC: National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, US Dept of Health and Human Services; 2012. Accessed September 27, 2021. https://www.cdc.gov/niosh/docs/2012-162/pdfs/2012-162.pdf
11. Baron PA. Direct-reading instruments for aerosols. A review. *Analyst*. 1994;119(1):35-40. doi:10.1039/an9941900035
12. Laohaudomchok W, Cavallari JM, Fang SC, et al. Assessment of occupational exposure to manganese and other metals in welding fumes by portable X-ray fluorescence spectrometer. *J Occup Env Hyg*. 2010;7(8):456-465. doi:10.1080/15459624.2010.485262
13. Seshadri DR, Li RT, Voos JE, et al. Wearable sensors for monitoring the physiological and biochemical profile of the athlete. *NPJ Digit Med*. 2019;2:72-88. doi:10.1038/s41746-019-0150-9
14. Tarar AA, Mohammad U, Srivastava SK. Wearable skins sensors and their challenges: a review of transdermal, optical, and mechanical sensors. *Biosensors*. 2020;10(6):56-78. doi:10.3390/bios10060056
15. Ometov A, Shubina V, Klus L, et al. A survey on wearable technology: history, state-of-the-art and current challenges. *Comput Networks*. 2020;193:1-37. doi:10.1016/j.comnet.2021.108074
16. Malik P, Gupta R, Malik V, Ameta RK. Emerging nanomaterials for improved biosensing. *Measurement: sensors*. 2021;16:10050. doi:10.1016/j.measen.2021.10050
17. Loncar-Turukalo T, Zdravevski E, Machado de Silva J, Chouvarda I, Trajkovik V. Literature on wearable technology for connected health: scoping review of research trends, advances, and barriers.

J Med Internet Res. 2019;21(9):e14017-e14036. doi:10.2196/14017
18. Khan S, Parkinson S, Grant I, Liu N, Mcguire S. Biometric systems utilizing health data from wearable devices: applications and future challenges in computer security. *ACM Comput Surv*. 2020;53(4):1-29. doi:10.1145/3400030
19. Kvedar J, Coye MJ, Everett W. Connected health: a review of technologies and strategies to improve patient care with telemedicine and telehealth. *Health Affair*. 2014;33(2):194-199. doi:10.1377/hlthaff.2013.0992
20. Sharma A, Badea M, Tiwari S, Marty JL. Wearable biosensors: an alternative and practical approach in healthcare and disease monitoring. *Molecules*. 2021;26:748-780. doi:10.3390/molecules26030748
21. Bonato P. Wearable sensors and systems. *IEEE Eng Med Biol Mag*. 2010;20(3):25-36. doi:10.1109/MEMB.2010.936554
22. Dinesen B, Nonnecke B, Lindeman D, et al. Personalized telehealth in the future: a global research agenda. *J Med Internet Res*. 2016;18(3):e53. doi:10.2196/jmir.5257
23. Ye S, Feng S, Huang L, Bian S. Recent progress in wearable biosensors: from healthcare monitoring to sports analytics. *Biosensors*. 2020;10(12):205-239. doi:10.3390/bios10120205
24. Cook DJ, Song W. Ambient intelligence and wearable computing: sensors on the body, in the home, and beyond. *J Ambient Intell Smart Environ*. 2009;1(2):83-86. doi:10.3233/AIS-2009-0014
25. Wilson HJ. Wearables in the Workplace. Harv Bus Rev. Accessed September 13, 2013. https://hbr.org/2013/09/wearables-in-the-workplace
26. Mettler T, Wulf J. Physiolytics at the workplace: affordances and constraints of wearables use from an employee's perspective. *Inform Syst J*. 2019;29(1):245-273. doi:10.1111/isj.12205
27. National Academies of Sciences, Engineering and Medicine. *Exposure science in the 21st century: a vision and a strategy*. National Academies Press; 2012. doi:10.17226/13507
28. Lioy P, Smith KR. A discussion of exposure science in the 21st century: a vision and a strategy. *Environ Health Perspect*. 2013;121:405-409. doi:10.1289/ehp.1206170
29. Horton J, Cameron A, Devaraj D, Hanson RT, Hajkowicz SA. Workplace safety futures: the impact of emerging technologies and platforms on work health and safety and workers; compensation over the next 20 years CSIRO Research Publications Repository, Canberra, Australia. 28-30; 2018. doi:10.25919/5d642c48416f5
30. Goede H, Kuijpers E, Krone T, et al. Future prospects of occupational exposure modelling of substances in the context of time-resolved sensor data. *Ann Work Expos Health*. 2021;65(3):246-254. doi:10.1093/annweh/wxaa102
31. Ozanich R. Chem/bio wearable sensors: current and future direction. *Pure Appl Chem*. 2018;90(10):1605-1613. doi:10.1515/pac-2018-0105
32. Direct Reading and Sensor Technologies National Institute for Occupational Safety and Health Web site. Accessed September 27, 2021. https://www.cdc.gov/niosh/topics/drst/default.html
33. Lee JH, Kim H, Hwang J-Y, et al. 3D printed, customizable, and multifunctional smart electronic eyeglasses for wearable healthcare systems and human–machine interfaces. *ACS Appl Mater Interfaces*. 2020;12(19):21424-21432. doi:10.1021/acsami.0c03110
34. Kim J, Kim M, Lee MS, et al. Wearable smart sensor systems integrated on soft contact lenses for wireless ocular diagnostics. *Nat Commun*. 2017;8:14997-15004. doi:10.1038/ncomms14997
35. Park J-H, Jang D-G, Park JW, Youm S-K. Wearable sensing of in-ear pressure for heart-rate monitoring with a piezo-electronic sensor. *Sensors*. 2015;15(9):23401-23417. doi:10.3390/s150923402
36. Gualandi I, Tessarolo M, Mariani F, Possanzini L, Scavetta E, Fraboni B. Textile chemical sensors based on conductive polymers for the analysis of sweat. *Polymers*. 2021;13(6):894-917. doi:10.3390/polym13060894
37. Bandodkar AJ, Jia W, Wang J. Tattoo-based wearable electrochemical devices: a review. *Electroanalysis*. 2015;27:562-572. doi:10.1002/elan.2014400537
38. Yetisen AK, Moreddu R, Seifi S, et al. Dermal tattoo biosensors for colorimetric metabolite detection. *Angew Chem Int Ed*. 2019;58(31):10506-10513. doi:10.1002/anie.201904416
39. Kim D-H, Lu N, Ma R, et al. Epidermal electronics. *Science*. 2011;333(6044):838-843. doi:10.1126/science.1206157
40. Kim Y-C, Park J-H, Prausnitz MR. Microneedles for drug and vaccine delivery. *Adv Drug Deliv Rev*. 2012;64:1547-1568. doi:10.1016/j.addr.2012.04.005
41. Zhang JXS, Hoshino K. *Molecular Sensors and Nanodevices: Principles, Designs and Applications in Biomedical Engineering*. William Andrew; 2014:415-465. https://www.elsevier.com/books/molecular-sensors-and-nanodevices/zhang/978-0-12-814862-4
42. Kalantar-zadeh K, Ha N, Ou JZ, Berean KJ. Ingestible sensors. *ACS Sens*. 2017;2:412-483. doi:10.1021/acssensors.7b00045
43. Guk K, Han G, Lim J, et al. Evolution of wearable devices with real-time disease monitoring for personalized healthcare. *Nanomaterials-Basel*. 2019;9:813-837. doi:10.3390/nano9060813
44. Zuidema C, Stebounova LV, Sousan S, et al. Estimating personal exposures from a multi-hazard sensor network. *J Expos Sci Environ Epidemiol*. 2020;30(6):1013-1022. doi:10.1038/s41370-019-0146-1
45. Rezagholi M, Mathiassen SE. Cost-efficient design of occupational exposure assessment strategies—a review. *Ann Occup Hyg*. 2010;54(8):858-868. doi:10.1093/annhyg/meq072
46. Evans DE, Heitbrink WA, Slavin TJ, Peters TM. Ultrafine and respirable particles in an automotive grey iron foundry. *Ann Occup Hyg*. 2008;52(1):9-21. doi:10.1093/annhyg/mei061
47. Dai X, Xia F, Wang Z, et al. A survey of intelligent information processing in wireless sensor network. In: Jia X, Wu J, He Y, eds. *Mobile Ad-hoc and Sensor Networks*. Springer; 2005:123-132. doi:10.1007/11599463_13
48. Bal M, Shen W, Ghenniwa H. Collaborative signal and information processing in wireless sensor networks: A review. In: 2009 IEEE International Conference on Systems, Man and Cybernetics; 2009:913:3151–3156. doi:10.1109/ICSMC.2009.5346152
49. Khan RA, Parthan AK. The state-of-the-art wireless body area sensor networks: a survey. *Int J Distrib Sens Netw*. 2018;14(4):2-23. doi:10.1177/1550147718768994
50. Svertoka E, Saafi S, Rusu-Casandra A, et al. Wearables for industrial work safety: a survey. *Sensors*. 2021;21:3844-3869. doi:10.3390/s21113844
51. Zeagler C. Where to wear it: functional, technical, and social considerations in on-body location for wearable technology 20 years of designing for wearability. In: Proceedings of the 2017 ACM International Symposium on Wearable Computers; 2017:150-157. doi:10.1145/3123021.3123042
52. Nayak R, Wang L, Padhye R. Electronic textiles for military personnel. In: Dias T, ed. *Electronic Textiles: Smart Fabrics and Wearable Technology*. 1st ed. Woodhead Publishing; 2015:239-256.
53. Wang C, Kim Y, Kim DG, Lee SH, Min SD. Smart helmet and insole sensors for near fall incidence recognition during descent of stairs. *Appl Sci*. 2020;10(7):2262-2278. doi:10.3390/app10072262
54. Campero-Jurado I, Marquez-Sanchez S, Quintanar-Gomez J, Rodriquez S, Corchado JM. Smart helmet 5.0 for industrial internet of things using artificial intelligence. *Sensors*. 2020;20(21):1-27. doi:10.3390/s202116241
55. Fridolfsson J, Arvidsson D, Doerks F, Kreidler TJ, Grau S. Workplace activity classification from shoe-based movement sensors. *BMC Biomed Eng*. 2020;2:8. doi:10.1186/s42490-020-00042-4

56. Consumer Product Safety Commission. Staff report: potential hazards associated with emerging and future technologies. Washington, DC: Consumer Product Safety Commission; 2017. Accessed October 5, 2021. https://www.cpsc.gov/content/potential-hazards-associated-with-emerging-and-future-technologies
57. Hazardous (classified) locations. 29 C.F.R. § 1910.307(a)(2). 2021. Accessed September 27, 2021. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.307
58. Schall MC, Sesek RF, Cavuto LA. Barriers to the adoption of wearable sensors in the workplace: a survey of occupational safety and health professionals. *Hum Factors*. 2018;60(3):351-362.
59. Awolusi I, Marks E, Hallowell M. Wearable technology for personalized construction safety monitoring and trending: review of applicable devices. *Automat Constr*. 2018;85:96-106. doi:10.1016/j.autcon.2017.10.010
60. Ahn CR, Lee S, Sun C, Jebelli H, Yang K, Choi B. Wearable sensing technology applications in construction safety and health. *J Constr Eng Manag*. 2019;145:03119007. doi:10.1061/(ASCE)CO.1943-7862.0001708
61. Kim S, Nussbaum MA. Performance evaluation of a wearable inertial motion capture system for capturing physical exposures during manual material handling tasks. *Ergonomics*. 2013;56(2):314-326. doi:10.1080/0014139.2012.742932
62. Stefana E, Marciano F, Rossi D, Cocca P, Tomasoni G. Wearable devices for ergonomics: a systematic literature review. *Sensors*. 2021;21:777-801. doi:10.3390/s21030777
63. Zhang M, Cao T, Zhao X. Applying sensor-based technology to improve construction safety management. *Sensors*. 2017;17(8):1841-1870. doi:10.3390/s17081841
64. Dogan O, Akcamete A. Detecting falls-from-height with wearable sensors and reducing consequences of occupational fall accidents leveraging IoT. In: Mutis I, Hartmann T, eds. *Advances in Informatics and Computing in Civil and Construction Engineering*. Springer; 2019:207-214. doi:10.1007/978-3-030-00220-6_25
65. Aryl A, Ghahramani A, Becerik-Gerber B. Monitoring fatigue in construction workers using physiological measurements. *Autom Constr*. 2017;82:154-165.
66. Maman ZS, Yazdi MAA, Cavuto LA. A data-driven approach to modeling physical fatigue in the workplace using wearable sensors. *Appl Ergon*. 2017;60:515-529. doi:10.1016/j.apergo.2017.02.001
67. Calvetti D, Mêda P, Gonçalves MC, Sousa H. Worker 4.0: the future of sensored construction sites. *Buildings*. 2020;10(10):169-190. doi:10.3390/buildings10100169
68. Permit-Required Confined Spaces. 29 C.F.R.§ 1910.146(b). 2021. Accessed September 27, 2021. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.146
69. Kiehl ZA, Durkee KT, Halverson KC, Christensen JC, Hellstern GF. Transforming work through human sensing: a confined space monitoring application. *Struct Health Monit*. 2020;19(1):186-201. doi:10.1177/1475921719840994
70. Silva TR, Coelho BN, Delabrida SE. Promising technologies and solutions for supporting human activities in confined space in industry. In: ICEIS 2021—23rd International Conference on Enterprise Information Systems. 2021;2:573-580. Accessed September 27, 2021. doi:10.5220/0010498205730580
71. Sammarco JJ, Paddock R, Fries EF, Karra VK. A technology review of smart sensors with wireless networks for applications in hazardous environments. Information Circular 9496. Publication No. 2007–114. Washington, DC: National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, US Dept of Health and Human Services; 2007. Accessed September 27, 2021. https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/2007-114.pdf
72. Mardonova M, Choi Y. Review of wearable device technology and its applications to the mining industry. *Energies*. 2018;11:547-565. doi:10.3390/en11030547
73. Mischler S, Coughanour V. *Continuous Personal Dust Monitor*. National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, US Depart of Health and Human Services; 2017. Accessed September 27, 2021. http://blogs.cdc.gov/niosh-science-blog/2017/02/03/pdm/
74. Djuric AM, Urbanic RJ, Rickli JL. A framework for collaborative robot (CoBot) integration in advanced manufacturing systems. *SAE Int J Mater Manuf*. 2016;9(2):457-464. doi:10.4271/2016-01-0337
75. Ramasubramanian AK, Aiman SM, Papakostas N. On using human activity recognition sensors to improve the performance of collaborative mobile manipulators: review and outlook. *Procedia CIRP*. 2020;97:211-216. doi:10.1016/j.procir.2020.05.227
76. Park S, Jayaraman S, Tao X. Adaptive and responsive textile structures. In: Tao X, ed. *Smart Fibers, Fabrics and Clothing: Fundamentals and Applications*. Woodhead Publishing Limited; 2001:226-245.
77. Hughes-Riley T, Dias T, Cork C. A historical review of the development of electronic textiles. *Fibers*. 2018;6(2):34-49. doi:10.3390/fib6020034
78. Shirakawa H, Louis EJ, MacDiarmid AG, Chiang CK, Heeger AJ. Synthesis of electrically conducting organic polymers: halogen derivatives of polyacetylene, (CH_x). *J Chem Soc, Chem Commun*. 1977;16:578-580. doi:10.1039/c39770000578
79. Cherenack K, von Pieterson L. Smart textiles: challenges and opportunities. *J Appl Physics*. 2012;112(9):091301. doi:10.1063/1.4742728
80. Radu T, Fay C, Lau KT, Waite R, Diamond D. Wearable sensing application—carbon dioxide monitoring for emergency personnel using wearable sensors. *Int J Electron and Commun Eng*. 2009;3(10):1794-1797. doi:10.5281/zenodo.1082965
81. Stoppa M, Chiolerio A. Wearable electronics and smart textiles: a critical review. *Sensors*. 2014;14(7):11957-11992. doi:10.3390/s140711957
82. Goncu-Berk G, Halsted T, Zhang R, Pan T. Therapeutic touch: reactive clothing for anxiety Atlanta, GA. Paper presented at: 14th EAI International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth '20); 2020:239-242. Accessed September 27, 2020. doi:10.1145/3421937.3421962
83. Bandodkar AJ, Jeerapan I, Wang J. Wearable chemical sensors: present challenges and future prospects. *ACS Sens*. 2016;1(5):464-482. doi:10.1021/acssensors.6b00250
84. Kuroda T, Takahasi H, Masuda A. Woven electronic textiles. In: Sazonov E, ed. *Wearable Sensors: Fundamentals, Implementation and Applications*. 2nd ed. Elsevier; 2021:29-84. doi:10.1016/B978-0-12-819246-7.00005-X
85. Berger H. Über das elektrenkephalogramm des menschen. *Archiv f. Psychiatrie*. 1929;87:527-570. doi:10.1007/BF01797193
86. Amendola S, Occhiuzzi C, Miozzi C, et al. UHF epidermal sensors: technology and applications. In: Sazonov E, ed. *Wearable Sensors: Fundamentals, Implementation and Applications*. 2nd ed. Elsevier; 2021:133-161. doi:10.1016/B978-0-12-819246-7.00005-X
87. Zhu X, Liu W, Shuang S, Nair M, Li C-Z. Intelligent tattoos, patches, and other wearable biosensors. In: Narayan RJ, ed. *Medical Biosensors for Point-of-Care (POC) Applications*. Woodhead Publishing; 2016:133-150.
88. Ribet F, Stemme G, Roxhed N. Real-time intradermal continuous glucose monitoring using a minimally invasive microneedle-based system. *Biomed Microdevices*. 2018;20(4):1-10. doi:10.1007/s10544-018-0349-6
89. Heikenfeld J, Jajack A, Rogers J, et al. Wearable sensors: modalities, challenges and prospects. *Lab Chip*. 2018;18(2):217-248. doi:10.1039/c7lc00914c
90. He R, Niu Y, Li Z, et al. A hydrogel microneedle patch for point-of-care testing based on skin interstitial fluid. *Adv Healthc Mater*. 2020;9(4):1901201. doi:10.1002/adhm.20190120

91. Kassanos P, Rosa BG, Keshavarz M, Yang G-Z. From wearables to implantables—clinical drive and technical challenges. In: Sazonov E, ed. *Wearable Sensors: Fundamentals, Implementation and Applications*. 2nd ed. Elsevier; 2021:29-84. doi:10.1016/B978-0-12-819246-7.00005-X
92. Nelson BD, Karipott SS, Wang Y, Ong KG. Wireless technologies for implantable devices. *Sensors*. 2020;20916:4604-4023. doi:10.3390/s2016404
93. Kmeic MM, Tse D, Mast JM, Ahmed R, Kuppusamy P. Implantable microchip containing oxygen-sensing paramagnetic crystals for long-term, repeated, and multisite in vivo oximetry. *Biomed Microdevices*. 2019;21:71-87. doi:10.1007/s10544-019-0421-x
94. Overview of device regulation. Food and Drug Administration Web site; 2020. Accessed September 27, 2021. https://www.fda.gov/medical-devices/device-advice-comprehensive-regulatory-assistance/overview-device-regulation
95. Jackson LL, Rosenberg HR. Preventing heat-related illness among agricultural workers. *J Agromed*. 2010;15:200-215. doi:10.1080/1059924X.2010.487021
96. Byrne C, Lim CL. The ingestible telemetric body core temperature. *Br J Sports Med*. 2007;41(3):126-133. doi:10.1136/bjsm2006.026344
97. Bongers CCWG, Hopman MTE, Eijsvogels TMH. Using an ingestible telemetric temperature pill to assess gastrointestinal temperature during exercise. *J Vis Exp*. 2015;104:e53258.
98. Stahn AC, Werner A, Opatz O, et al. Increased core body temperature in astronauts during long-duration space missing. *Sci Rep*. 2017;7:16180-16188. doi:10.1038/s41598-017-15560-w
99. National Aeronautics and Space Administration. Ingestible thermometer pills aids athletes in beating the heat. Spinoff. Washington, DC: National Aeronautics and Space Administration; 2006:6-10. Accessed September 27, 2021. https://www.nasa.gov/pdf/164449main_spinoff_06.pdf
100. Lazaro P, Momayez M. Health stress in hot underground mines: a brief literature review. *Min Metal Expl*. 2021;38:497-508. doi:10.1007/s42461-020-00324-4
101. Monnard CR, Fares E-J, Calonne J, et al. Issues in continuous 24-hr core body temperature monitoring in humans using ingestible capsule telemetric sensor. *Front Endocrinol (Lausanne)*. 2017;13(8):130-143. doi:10.3389/fendo.2017.00130
102. Lee SMC, Williams WJ, Schneider SM. Core temperature measurement during supine exercise: esophageal, rectal, and intestinal temperature. *Aviat Space Environ Med*. 2000;71(9):939-945.
103. Ajunwa I, Crawford K, Schultz J. Limitless worker surveillance. *Calif Law Review*. 2017;105(3):735-776. doi:10.15779/Z38BR8MF94
104. Spook SM, Koolhaus W, Bültmann U, Brouwer S. Implementing sensor technology applications for workplace health promotion: a needs assessment among workers with physically demanding work. *BMC Public Health*. 2019;19:1100-1109. doi:10.1186/s12889-019-7364-2
105. Jacobs JV, Hettinger LJ, Huang Y-H, et al. Employee acceptance of wearable technology in the workplace. *Appl Ergon*. 2019;78:148-156. doi:10.1016/j.apergo.2019.03.003
106. Nnaji C, Awolusi I, Park J, Albert A. Wearable sensing devices: towards the development of a personalized system for construction safety and health risk mitigation. *Sensors*. 2021;21:682-705. doi:10.3390/s21030682
107. Häikiö J, Kallio J, Mäkelä S-M, Keränen J. IoT-based safety monitoring from the perspective of construction site workers. *Int J Occup Environ Saf*. 2020;4(1):1-14. doi:10.24840/2184-0954_004.001_0001
108. Choi B, Hwang S, Lee S. What drives construction workers' acceptance of wearable technologies in the workplace? Indoor localization and wearable health devices for occupational safety and health. *Automat Constr*. 2017;84:31-41. doi:10.1016/j.autcon.2017.08.005
109. Yaseen M, Saleem K, Orgun MA, et al. Secure sensors data acquisition and communication in eHealthcare: review on the state of the art. *Telemat Inform*. 2018;35(4):702-726. doi:10.1016/j.tele.2017.08.005
110. Besher KM, Subah Z, Ali MZ. IoT sensor-initiated healthcare data security. *IEEE Sensors J*. 2021;21(10):11977-11982. doi:10.1109/JSEN.2020.3013634
111. le Feber M, Jadoenathmisier T, Goede H, Kuijers E, Pronk A. Ethics and privacy considerations before deploying sensor technologies for exposure assessment in the workplace: results of a structured discussion amongst Dutch stakeholders. *Ann Work Expo Health*. 2021;65(1):3-10. doi:10.1093/annweh/wxaa093
112. Marchant GE. What are the best practices for ethical use of nanosensors for worker surveillance? *AMA J Ethics*. 2019;21(4):E356-E362. doi:10.1001/amajethics.2019.356
113. Kandasamy K, Srinivas S, Achuthan K, Rangan VP. IoT cyber risk: a holistic analysis of cyber risk assessment frameworks, risk vectors, and risk ranking process. *EURASIP J Info Security*. 2020;21:8. doi:10.1186/s13635-020-00111-0
114. Occupational Noise Exposure 29 C.F.R. § 1910.95. Accessed September 27, 2021. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.95
115. Lowering miners' exposure to respirable coal mine dust including continuous personal dust monitors; final rule. Fed Regist. 2014;79(84):24814-24994. Accessed September 27, 2021. https://www.govinfo.gov/content/pkg/FR-2014-05-01/pdf/2014-09084.pdf

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