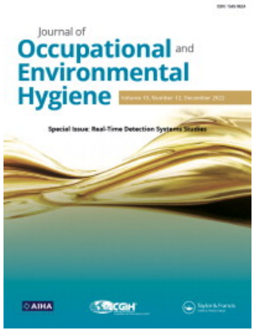

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Direct-reading instruments for aerosols: A review for occupational health and safety professionals part 1: Instruments and good practices

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ABSTRACT

With advances in technology, there are an increasing number of direct-reading instruments available to occupational health and safety professionals to evaluate occupational aerosol exposures. Despite the wide array of direct-reading instruments available to professionals, the adoption of direct-reading technology to monitor workplace exposures has been limited, partly due to a lack of knowledge on how the instruments operate, how to select an appropriate instrument, and challenges in data analysis techniques. This paper presents a review of direct-reading aerosol instruments available to occupational health and safety professionals, describes the principles of operation, guides instrument selection based on the workplace and exposure, and discusses data analysis techniques to overcome these barriers to adoption. This paper does not cover all direct-reading instruments for aerosols but only those that an occupational health and safety professional could use in a workplace to evaluate exposures. Therefore, this paper focuses on instruments that have the most potential for workplace use due to their robustness, past workplace use, and price with regard to return on investment. The instruments covered in this paper include those that measure aerosol number concentration, mass concentration, and aerosol size distributions.

KEYWORDS

Aerosols; analyzing data; direct-reading instruments; optical particle counters; real-time monitors

Introduction

Direct-reading instruments (DRIs) for aerosols have been available for decades (Baron 1994; Pui 1996; Lowther et al. 2019). A DRI, as applied to the assessment of workplace aerosol exposures, is an electronic instrument that transforms the size and/or concentration (number, mass, and/or surface area) of an aerosol into a voltage signal that can be displayed and recorded on a "real-time" basis established by the sample rate of the DRI. A DRI, therefore, does not require that a sample be taken on supporting media or analyzed by a laboratory, which minimizes the time required to obtain aerosol exposure information (Coffey and Pearce 2010). In this paper, the term DRI applies exclusively to an aerosol DRI. Occupational health and safety professionals have commonly used DRIs for assessing control effectiveness and determining aerosol concentrations before collecting personal samples so that samples are not overloaded (Bisesi 2004). Many occupational health and safety professionals are impelled to use time-integrated samples that can be easily compared to occupational exposure limits in the form of a time-weighted average (TWA). While TWA samples provide a good understanding of the cumulative exposure, they cannot elucidate the temporal or spatial distribution of concentrations measured within the cumulative measurements. Understanding worker exposure is complex because of the variability across time, shifts, and location (Ramachandran 2008). Many workplace exposures exhibit substantial variability, both between and within workers, that may not be adequately captured by a TWA measurement (Rappaport 1991). Furthermore, analysis of gravimetric samples can be expensive and slow, resulting in a limited number of samples collected. Occupational health and safety professionals can use DRIs and

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TWA samples as a complementary approach to exposure assessment.

Even though DRIs for aerosols have been available tools for professionals for decades (Baron 1994; Pui 1996), hesitancy in expanding their use in the workplace is consistent with the adoption (also known as diffusion) of new technologies in other areas (Baron 1994; Hall and Khan 2002). Barriers to adoption include: inadequate understanding of the technology; the challenge of correctly choosing an instrument; and issues with properly analyzing the output data from the instrument. These barriers to adoption must be considered when comparing the cost of new technology to traditional methodologies and weighed against the benefits to make a business case for the adoption of the technology.

Previous review articles addressing aerosol DRIs have focused on describing both workplace and laboratory DRIs (Baron 1994; Pui 1996; Lowther et al. 2019), with an emphasis on laboratory instruments that occupational health and safety professionals typically do not use or are not able to access. This review of DRIs focuses on instruments that have the most potential for workplace use due to their robustness, past workplace use, and price with regard to return on investment. A State-of-the-Art review type (Grant and Booth 2009) was used to limit the literature included in this review to focus this review on those priorities of robustness, past workplace use, and price. The applicable DRIs are briefly described and guidance to select an appropriate DRI is introduced. A section on how to analyze the data from a DRI is also included. This review aims to inform the occupational health and safety community of the capabilities, limitations, and data analysis techniques associated with DRIs and expand our understanding of how to apply these useful instruments to identifying and solving aerosol problems in the workplace.

Workplace DRIs

The physical principle by which an aerosol or individual airborne particle is detected ultimately determines the response type (particle count or concentration) that is measured. Light scattering and electrical mobility are the two most common principles applied to DRIs used for the assessment of a workplace aerosol.

Light scattering

The most commonly applied principle for DRIs small enough to be field portable is light scattering (Hinds 1999). This well-known effect has been adapted to DRIs by applying a laser source and a receiving photosensor to detect scattered light. Optical particle counters (OPCs) use scattered light to detect and size individual particles and can provide a total number concentration and particle size distribution (Görner et al. 2012). After increasing particle size, condensation particle counters (CPCs) use light scattering to detect particles and provide a total number concentration. Aerosol photometers detect all scattered light from the aerosols and provide a total mass concentration (O'Shaughnessy and Slagley 2002).

Optical particle counters

Because air can also scatter light, the particle size-resolving capability of OPCs is ultimately limited by the intensity of the light source and the sampling flow rate (Gebhart 2001). Contemporary OPCs contain a laser light source to maximize light intensity that could, theoretically, resolve particles down to approximately 50 nm. However, OPCs developed as DRIs for use in occupational settings incorporate a flow rate high enough to obtain reliable count concentrations that result in the lowest size channel reporting particles within the range of 0.25–0.30 μm. An OPC can detect a large range of particle sizes up to approximately 25 μm. The particle size measurement resulting from an OPC is referred to as "optical diameter" or better "light-scattering equivalent diameter" because of the optical technique applied to the OPC, which is considered to be equivalent to the particle's geometric diameter (Görner et al. 2012). OPCs are generally calibrated with perfectly spherical particles of known composition and size distribution. The effect on the response of the OPC in terms of light-scattering diameter can be significant (Buettner 1990). A better process of the calibration of OPCs response for different particles in terms of optical response has been investigated (Walser et al. 2017). In addition, the light-scattering equivalent diameter is distinguished from a particle aerodynamic diameter, which is applied to the performance of size-selective aerosol samplers such as the respirable cyclone. Therefore, particle diameters measured using OPCs must be converted to aerodynamic diameters if used to determine inhalable and respirable aerosol concentrations (Görner et al. 2012). Such a conversion may be applied to predict mass-based concentrations from the count-based concentrations measured with an OPC. For example, Evans et al. (2008) utilized an OPC to determine respirable particle concentrations surveyed throughout an automotive iron foundry. Grimm and Eatough (2009) have also demonstrated the use of an OPC to obtain accurate ambient particulate matter mass concentrations.

Depending on the device, particle counts are applied to six or more size bins (also called channels) to allow for the determination of the size distribution of the aerosol particles. In addition to its diameter, the nature of the light scattered by a particle (for a particle OPC light wavelength and optical detector geometry) is also influenced by its refractive index (RI) and, to some extent, shape (Quenzel 1969; Hinds 1999). Since OPCs are calibrated with the use of polystyrene latex spheres, they are therefore most accurate for placing a counted particle in the proper size bin when measuring aerosols with a similar RI of 1.61 and shape (Marx and Mulholland 1983; Liu and Daum 2000). Schmoll et al. (2010) evaluated the effect of RI on OPC sizing accuracy for aerosols with RIs ranging from 1.46 to 3.01. They demonstrated that aerosols with RIs > 1.61 can be undersized by an OPC such as titanium dioxide (2.62) and iron oxide (3.01). While the details of the theories of light-scattering response from particles and conversions in terms of particle sizes are not the focus of this article, occupational and environmental hygiene professionals should be always aware of the possible biases introduced by the differences of particles used for calibrating these instruments and the aerosol particles of interest.

Condensation particle counter

A CPC also uses light-scattering techniques similar to an OPC to count particles. As inferred in its name, CPCs utilize the condensation of vapor (originally butanol, but now also water) onto particles to increase their diameter (Matson et al. 2004; Zhu et al. 2006). This added feature (to grow small particles a few nm in diameter) allows the light scattered by particles $< 0.25\,\mu$m to be detected. Field portable CPCs have been developed, which extend the measurable particle size range into a range lower than that of OPCs, but they do not size the aerosol into bins. However, Schmoll et al. (2010) evaluated an approach for combining measurements made with a co-located CPC and OPC, which in effect, created a size bin from CPC measurements below the bins associated with the OPC. Methner et al. (2010), Methner, Hodson, and Geraci (2010), and Methner et al. (2012) also utilized a combined CPC and OPC as part of a proposed best-practice technique for fully evaluating workplaces containing nanoparticles. A large number of concentrations of fine aerosols (greater than 100,000 particles/cm^3) can cause the instrument to over-range, limiting the use of CPCs in many workplaces (Park et al. 2011; Vosburgh et al. 2011). To extend the range of the CPC, some investigators (Peters et al. 2006; Heitbrink et al. 2007; Evans et al. 2008; Vosburgh et al. 2011) used a dilutor for the CPC and the calculation of a dilution factor described by Vosburgh et al. (2011).

Aerosol photometers

Aerosol photometers (or "nephelometers") detect the light scattered from all particles within the "view volume" of the instruments and convert the signal detected by the photosensor directly into mass concentration for display and recording (Görner et al. 1995). Photometers, therefore, utilize light scattering as an indirect measure of aerosol mass. Most current photometers can also be fitted with a manufacturer-provided size-selective inlet to only allow particles of specific size ranges (for example, respirable) to enter the view volume if sensing that size fraction is desired (Dasch et al. 2005; Benton-Vitz and Volckens 2008; Liu and Hammond 2010). Others have used external cyclones to define the respirable fraction (Evans et al. 2010). A modified aerosol photometer is also available that further processes the light signal read by the receiving photodiode into a photometric signal for measuring mass concentration as well as single particle pulses for measuring particle size (TSI 2012). Mass concentrations can then be reported for various size fractions.

Like the OPC, a photometer is most accurate when measuring the aerosol type used for its calibration, and is influenced by aerosol RI and shape. Photometers are also influenced by high ambient relative humidity (Wu et al. 2005). Historically, photometers have been calibrated with Arizona Road Dust (ISO Test Dust, Powder Technology Inc., Arden Hills, MN) because it is well characterized and has an RI (1.54) and density (2.65 g/cm^3) that are similar to a wide variety of inorganic dust (Jiang et al. 2011). In most circumstances, side-by-side comparisons of photometer response and mass concentration measured gravimetrically should be conducted to determine a calibration factor between the two measurement techniques (Smith et al. 1987; Taylor and Reynolds 2001). A correction factor derived from such a comparison can then be applied to currently available photometers. Correction factors for the specific size fraction can also be developed using gravimetric sampling with a size segregator, such as a cyclone (Afshar-Mohajer et al. 2020).

Light scatters off particles at different angles depending on their size (Görner et al. 2012). This

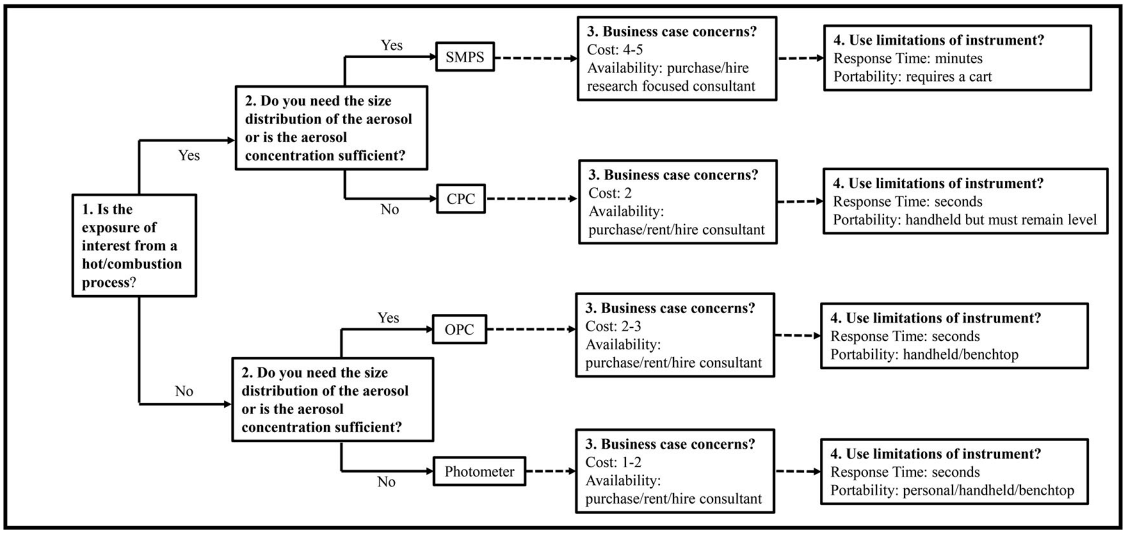

Figure 1. Considerations for choosing the appropriate aerosol DRI. For cost values 1 represents under \$5,000, 2 represents \$5,001–\$10,000. 3 represents \$10,001–\$20,000, 4 represents \$20,001–\$30,000, 5 represents greater than \$30,000.

phenomenon is utilized by an OPC to size particles but is a potential source of photometer error. As demonstrated by O'Shaughnessy and Slagley (2002), particles near 2 μm scatter light that produces the highest photosensor response with a steep reduction in response for particles smaller and larger than 2 μm. Photometer response is therefore not only associated with the aerosol concentration but also with its size distribution. For example, measurements made near an aerosol source may have high concentration and large size distribution that together result in certain instrument responses. Measurements then made further away from the source will show a lower concentration that is partially the result of a true reduction in concentration and partially resulting from a shift in the size distribution toward smaller particles that remain in the air and within sizes that produce a lower response.

Electrical mobility

Scanning mobility particle sizers

A scanning (or sequential) mobility particle sizer (SMPS) measures the number concentration by the size of particles between approximately 10–800 nm. The SMPS is composed of a differential mobility analyzer (DMA) and a CPC. As the submicron aerosol enters the DMA, it obtains a bipolar charge and is then sent through a column forming an electric field. The electric field causes particles of only certain electrical mobility, and, therefore, a certain size, to pass through the column and into the CPC to be counted. The electrode is cycled through a range of charges during the SMPS measurement process to obtain the number of concentrations in bins covering the range of the instrument (Flagan 1998). There are laboratory and workplace versions of SMPSs. Laboratory versions have more bins but workplace versions are more robust. The size of workplace SMPSs varies, with the lightest version being approximately 4.5 kg (Vo et al. 2018; Kulkarni et al. 2016) but most weighing significantly more, therefore requiring the use of a cart to move the SMPS to various monitoring locations in a workplace (Baron 2001).

Selecting an appropriate DRI

A wide variety of DRIs is currently available. The variety is associated with the physical principles applied to measure an aerosol as well as the portability and cost of the DRI. To sort through the options of instruments, four important questions must first be answered regarding the workplace or process to be addressed (Figure 1).

1. Is the exposure of interest from a hot/combustion process? Particle sources and method of generation determine particle size because particles < 1 µm are generated from combustion products, whereas particles > 1 µm are generated from abrasive, atomization, or other mechanical processes (John 2011). Careful consideration of the particle size and data application is necessary when selecting an appropriate instrument.
2. Do you need the size distribution of the aerosol or is the aerosol concentration sufficient? Knowledge of aerosol size distribution is useful for multiple situations. For example, aerosol size

distribution may provide additional information for a previously unknown hazard (Heitbrink et al. 2007; Vosburgh et al. 2011) or inform an occupational health and safety professional of processes that create bimodal distributions, such as occurs in the wood products and mining industries (Cooper et al. 2017; da Silveira Fleck et al. 2018). The obvious advantage of using an OPC vs. a photometer is its ability to size discriminate. Its use will therefore allow the user to determine the distribution of particle sizes as well as changes in that distribution over time or space. For example, Peters et al. (2008) used an OPC in conjunction with a CPC to determine nanoparticle number concentration and both the total and respirable mass concentrations over time during repetitive worker activities. From the resulting data time series, they were able to determine that the mass concentrations were directly related to worker activities but the nanoparticle number concentrations were not.

3. Can a business case be made for using the aerosol DRI? Availability of these DRIs due to cost is always an important consideration. Some models of OPCs, photometers, and CPCs can be rented. The rental costs vary by DRI and rental company. However, in 2022, no industrial hygiene equipment rental company rents SMPSs, therefore, a research-focused consultant who has previously purchased one would be needed. As for purchasing the instruments, the costs vary widely (Figure 1). Although both OPCs and photometers can cost between \$2,000 and \$20,000, recent advances in OPC technology have resulted in the development of small, lightweight OPCs that can be purchased for less than \$500 (Sousan et al. 2016; Zuidema et al. 2019). Recent research demonstrated the effective use of these small OPCs as part of a large network to provide simultaneous measurements in a high number of places or on a high number of people (Thomas et al. 2018; Magen Molho et al. 2019; Quinn et al. 2020). Although workplace models of SMPSs have come down in price, unless they are used often so there is a return on investment, many SMPSs are still beyond the budget of most non-research occupational health and safety professionals.
4. What are the DRI use limitations in terms of response time and portability? A more expensive DRI is not always the better DRI. Using limitations such as response time and portability can also be important. For example, the primary difference between an OPC and a photometer is that the OPC can size-resolve aerosols whereas the photometer cannot. However, because it takes a certain minimum amount of time to count particles and place them in appropriate size bins (6 sec–1 min), an OPC cannot produce a continuous data stream. However, photometer response is essentially continuous—an analog voltage output proportional to concentration is a typically available feature that can produce a data stream with a resolution as fast as the analog-to-digital conversion process of the personal computer and converter. Therefore, a photometer may be the better choice when it is desired to capture sudden changes in aerosol concentration resulting from worker activities (Dahm et al. 2013). Handheld CPCs have a portability limitation in that they must remain level while being used because, if tipped, the liquid used for condensation will flood the area in front of the laser resulting in interrupted measurements (Baron 2001). New designs may overcome this limitation (Hering et al. 2019). Like all handheld DRIs, use of a handheld CPC during a work shift is limited by battery life, but also by the use rate of the liquid reservoir, which can be less than 8 hr.

Once a DRI has been chosen, there are also additional considerations such as the over-ranging of the instrument and data management. All DRIs have an upper limit of the particles in an aerosol they can sense. If the number or mass concentration is greater than that of the instrument, then over-ranging occurs and steps must be taken to address the issue. For example, the number concentration near a welding station is greater than the maximum measurable number concentrations of many hand-held CPCs (Stephenson et al. 2003). Aerosol DRI use is also dependent on digitally capturing, storing, and retrieving a stream of data; a process dependent on external and/or internal software for which the ease of use may also be considered, but is not covered here. Occupational safety and health professionals should determine their employer’s limits including the use of externally sourced instrument software due to an organization’s concern about cybersecurity.

Once the DRI has been chosen, it is important to follow the manufacturer’s instructions with regard to instrument use (TSI 2002, 2013). Important considerations such as warm-up times, storage recommendations, and factory calibration recommendations are specific to the individual model of DRI. Before each use, it is good practice for all DRIs to have a high-efficiency particulate air (HEPA) filter placed on the inlet for a few minutes to verify that the instrument is measuring zero particles when no aerosol is present. Most DRIs have a specific make and model of HEPA filter that is recommended, which is often called a zero filter. It can be important to use the specified zero filter so an increased pressure drop issue is not caused during the verification (TSI 2002, 2013).

Analyzing DRI data

The generation of new, valuable information and ultimately new knowledge should be the goal of any monitoring activity in an occupational environment. To achieve new information and knowledge, DRI datasets must be inspected, investigated, and often processed.

Compared to data points from time-integrated samples, datasets from DRIs have additional layers of information. The distribution of concentration levels during the monitoring event and the consequent evolution of the concentration levels over time are two distinct additional layers. How occupational health and safety professionals decide to extract valuable information using all the layers of data is critical. The type of investigative or statistical approach the occupational health and safety professional decides to adopt will determine the quality of the information and knowledge generated. The identification and use of the right statistical approach are not easy tasks and, if, in doubt, the occupational health and safety professional should consult with a statistician.

Descriptive statistics and plotting

The first step in any analysis of a dataset from a DRI is to create a graph that can provide visual evidence of peaks and trends (Brouwer et al. 2004; Klein Entink et al. 2011; O'Shaughnessy and Cavanaugh 2015). An occupational health and safety professional might decide to use a logarithmic scale for the concentration levels (y-axis) if the levels span across different orders of magnitude and there is an interest in low-concentration variability. Following a visual inspection of the dataset, descriptive statistics can be conducted on the data with the generation of measures such as arithmetic mean and standard deviation. Basic spreadsheet software also allows the occupational health and safety professional to investigate the skewness of the distribution of the data in a dataset. This analysis can reveal the underlying distribution of the dataset (lognormal or multi-modal distribution) and it can lead the occupational health and safety professional to calculate additional descriptive statistics such as the geometric mean and geometric standard deviation. These statistics might provide a better representation of the central tendency and spread of the dataset, although the standard deviation and GSD must be interpreted with caution as autocorrelation can cause both to be underestimated (Houseman and Virji 2017). In addition, a normal or lognormal histogram plot of the data in the dataset can indicate the presence of spurious data points or statistical outliers. These points are generally representative of extremely high concentration levels or spikes in the concentration level. Although from a statistical perspective, these points can be considered outliers and should be carefully considered before any advanced statistical or modeling approach is attempted; however, these same points can be extremely informative of worst-case scenarios in terms of aerosol concentration. The occupational health and safety professional should decide to focus the attention on the spurious datapoints or remove them from additional analysis based on the objective of the investigation. In the case where the focus is on the identification of the worst-case conditions, the combination of DRIs and video monitoring can be pursued for a comprehensive analysis (Cecala et al. 2013; Patts et al. 2020). Other basic analyses of a dataset from a DRI include: (1) the subdivision of the dataset in logical periods representative of different intervals/tasks in the workplace; and (2) the analysis of the evolution of the aerosol concentration level in time using a moving average or the calculation of the mean and standard deviation for short periods (i.e., 15 min).

In the case of networks of aerosol DRIs in a workplace, these systems can provide the temporal and spatial patterns of occupational hazards that traditional industrial hygiene approaches with cumulative sampling approaches cannot (Koehler et al. 2017; Zuidema et al. 2019). The large amount of data resulting from these networks has also spurred the development of data analysis procedures such as machine learning techniques (Alsheikh et al. 2014; Hu et al. 2017).

Hazard maps can offer insight into the aerosol sources, areas of high level, variability in concentrations near different activities, and adoption of control technologies. Hazard mapping is not without limitations since it relies on interpolation and extrapolation of information based on the number of nodes (monitors) used (Peters et al. 2006; Berman et al. 2018; Thomas et al. 2018).

Hypothesis testing and time series modeling

The occupational health and safety professional might use a dataset from DRIs to create a model for basic inferences. The inference can be the prediction of a future condition or the statistical comparison of a sampling session to an exposure limit or another session. The use of datasets from DRIs to compare two, or multiple, conditions is indeed a possible application of these devices. Statistical analysis, such as a t-test or an analysis of variance (ANOVA), might be employed for this comparison but an occupational health and safety professional must be aware of the risk of autocorrelation for measurements in one dataset, especially when the monitoring rate is quite high. In this case, the assumption of independence of the measurements for the t-test and ANOVA is violated. This issue can be quite common for datasets from DRIs in general and specifically aerosol monitors (Klein Entink et al. 2011; O'Shaughnessy and Cavanaugh 2015). The autocorrelation issue might be reduced by averaging the real-time data in batches. O'Brien et al. (1989) also suggested a method in which regression analysis was performed on the difference between the predicted and observed measurements offset by one, two, or three readings to determine the time between readings in which autocorrelation was no longer evident.

A possible approach to account for autocorrelation patterns is the adoption of autoregressive integrated moving average (ARIMA) models (Klein Entink et al. 2011). The process of adopting an ARIMA model starts with an analysis of the stationarity of the time series, which evaluates whether statistical properties remain constant over time, and autocorrelation significance. Then an ARIMA model can be identified and applied to the data. This approach can be used to statistically investigate a potential rise of the concentration in a specific period during the monitoring event. A simpler and more effective alternative approach to ARIMA models has been proposed comparing the mean levels of datasets comprised of autocorrelated time series (O'Shaughnessy and Cavanaugh 2015) that are presumed to follow the first-order autoregressive (AR) model. The approach evaluates the datasets for autocorrelation and creates an equivalent sample size accounting for the autocorrelation if present. In this way, a one-sample t-test using an exposure limit or a two-sample t-test can be properly conducted. Finally, in an exploratory study focused on data from DRIs measuring ultrafine aerosols, a Bayesian probabilistic approach was used with the intent to transform the time series in probability distributions (Clerc et al. 2013). Two or more resulting probability distributions can then be compared for inferences. Houseman and Virji (2017) expanded on this approach by incorporating a spline-based method to model autocorrelation that does not require a prior assumption of the autocorrelation structure. Their method also allows for the incorporation of left-censored data (below the limit of detection) by integrating over the left tail of the data distribution. Overall, their Bayesian model developed a good fit for observed real-time data despite being non-stationary that provided representative means and standard deviations of task exposures measured with a DRI.

Time-resolved DRI data can be used for modeling the exposure of workers to aerosols and three general approaches have been proposed (Goede et al. 2021): (1) enrichment of existing time-integrated exposure models; (2) new high-resolution (in time and space) empirical models; and (3) new "occupational dispersion" models. The first approach, the most applicable for the near future, is the realization that occupational exposure limits for aerosols are mostly based on TWA measured with time-integrated methods and models. The use of time-resolved data from DRIs can help develop exposure profiles or identify similar exposure groups. The second approach proposes the adoption of new statistical models such as ARIMA or other techniques for less stationary time series. Finally, the last approach will use an improved understanding of the dispersion of aerosols in the workplace using, for example, computational fluid dynamics and the knowledge of the position of the workers relative to the aerosol source.

Summary

DRIs have the potential to assist occupational health and safety professionals to tackle complex workplace safety and health issues. While TWA samples provide a good understanding of cumulative exposure, the ability of DRIs to address temporal and/or spatial distributions of concentrations allows them to assist occupational health and safety professionals in a way a TWA measurement cannot. However, the barriers to the adoption of DRIs must be addressed. First, understanding the physical principle by which an aerosol is measured by a DRI must be understood. Then other instrument-specific characteristics should be considered to allow for the selection of an appropriate DRI. DRIs provide much larger amounts of data than TWA measurements and correctly analyzing that data is key to a DRIs usefulness. Data analysis of DRI data should always begin with descriptive statistics and plotting of the data. Then hypothesis testing and time-series modeling can be conducted with the correct steps. Once those barriers to adoption are addressed, a business case for the adoption of DRI to address aerosol concerns in the workplace can be made.

Disclaimer

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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