Direct-reading instruments for aerosols: A review for occupational health and safety professionals part 2: Applications

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ABSTRACT
Direct reading instruments (DRIs) for aerosols have been used in industrial hygiene practice for many years, but their potential has not been fully realized by many occupational health and safety professionals. Although some DRIs quantify other metrics, this article will primarily focus on DRIs that measure aerosol number, size, or mass. This review addresses three applications of aerosol DRIs that occupational health and safety professionals can use to discern, characterize, and document exposure conditions and resolve aerosol-related problems in the workplace. The most common application of aerosol DRIs is the evaluation of engineering controls. Examples are provided for many types of workplaces and situations including construction, agriculture, mining, conventional manufacturing, advanced manufacturing (nanoparticle technology and additive manufacturing), and non-industrial sites. Aerosol DRIs can help identify the effectiveness of existing controls and, as needed, develop new strategies to reduce potential aerosol exposures. Aerosol concentration mapping (ACM) using DRI data can focus attention on emission sources in the workplace spatially illustrate the effectiveness of controls and constructively convey concerns to management and workers. Examples and good practices of ACM are included. Video Exposure Monitoring (VEM) is another useful technique in which video photography is synced with the concentration output of an aerosol DRI. This combination allows the occupational health and safety professional to see what tasks, environmental situations, and/or worker actions contribute to aerosol concentration and potential exposure. VEM can help identify factors responsible for temporal variations in concentration. VEM can assist with training, engage workers, convince managers about necessary remedial actions, and provide for continuous improvement of the workplace environment. Although using DRIs for control evaluation, ACM and VEM can be time-consuming, the resulting information can provide useful data to prompt needed action by employers and employees. Other barriers to adoption include privacy and security issues in some worksites. This review seeks to provide information so occupational health and safety professionals can better understand and effectively use these powerful applications of aerosol DRIs.

KEYWORDS
Aerosol concentration mapping; aerosols; control evaluation; direct-reading instruments; video exposure monitoring

Introduction
Direct-reading instruments (DRIs) specifically for aerosol measurement (which will be referred to as DRIs for the rest of the paper) have been available for decades (Baron 1994; Pui 1996; Lowther et al. 2019). Despite their enduring presence in our instrument arsenal, many occupational health and safety professionals have only used DRIs for determining aerosol concentrations before collecting personal samples so that personal samples are not overloaded (Bisesi 2004). Nevertheless, industrial hygiene research has shown that DRIs for aerosols can be used to deal with complex industrial hygiene problems. As work environments become more complex, understanding variability across time, shifts, and location has become more important (Ramachandran 2008). Being able to address temporal or spatial concentration differences in real time has allowed DRIs to be used to answer
industrial hygiene questions that cannot be answered with the use of traditional time-weighted average (TWA) samples.

Previous review articles addressing aerosol DRIs have focused on describing specific DRIs (Baron 1994; Pui 1996; Lowther et al. 2019). This article will principally address DRIs that measure aerosol number, size, or mass. To introduce potential applications of DRIs, this review will focus on three ways that DRIs have been used in workplaces. DRIs have been used successfully to evaluate controls, conduct aerosol concentration mapping (ACM), and perform video exposure monitoring (VEM). Over the years, the evaluation of controls has been one of the most common and productive applications of DRIs. Although not as common, ACM is increasing in the workplace because it creates an easy-to-understand visual. By maximizing the power of DRIs, VEM allows for a systematic approach to different industrial hygiene problems and provides permanent documentation that exceeds typical industrial hygiene field notes (Gressel et al. 1992; McGlothlin 2005; Prezant 2011). Part 1 of this two-part review of DRIs focuses on the proper selection and description of available DRIs and provides information on best practices for analyzing data obtained from DRIs. Part 2 aims to inform the industrial hygiene community on methods used to apply DRIs to identify and address aerosol exposures in the workplace.

### Strategy and scope of literature search

An extensive search was conducted of the indices for the following key journals: Journal of Occupational and Environmental Hygiene and its predecessors (AIHA Journal; AIHAJ - American Industrial Hygiene Association; American Industrial Hygiene Association Journal; American Industrial Hygiene Association Quarterly); Applied Occupational and Environmental Hygiene and its predecessor Applied Industrial Hygiene; Annals of Work Exposures and Health and its predecessor The Annals of Occupational Hygiene; and Aerosol Science and Technology. The websites for the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA) were checked along with Google Scholar. In addition, the databases PubMed and Web of Science were searched for studies written in English. With no restriction on starting date, the ending date for the search was July 1, 2022. For all of these indices, websites, and databases, exemplary search terms included individually or in combination: “aerosol direct reading instrument,” “aerosol real-time instrument,” “evaluation of controls,” “workplace aerosol control,” “additive manufacturing” “workplace mapping,” “video exposure monitoring,” and “video monitoring.” Selected studies were limited to workplaces and, in the control section, articles were grouped by workplace category. Studies were included if the authors noted that they used DRIs for evaluating engineering controls for aerosols and/or mapping aerosol concentrations and/or using video exposure monitoring for aerosol concentrations. The references of included articles were inspected for additional articles. Biological aerosols were not included. The inclusion of articles is expansive but is limited in that the search was primarily made by one author and supplemented and reviewed by the other authors.

### Evaluation of engineering controls

DRIs have been used to develop, assess, and improve the adequacy of control technologies, refine source identification and improve assessment methods. Studies before the 1990s addressed controls in mining (Blackford and Harris 1978) and construction (O’Brien et al. 1989). The majority of studies since 1990 addressed some type of worksite local exhaust ventilation (LEV) and/or general ventilation across a wide range of workplaces.

### Evaluating controls in workplaces

#### Construction settings

Many studies focused on construction-related aerosols and control devices. Debia et al. (2014) addressed the adequacy and positioning of movable hoods for apprentice welders. They concluded that slot hoods should be replaced with cone hoods close to the source and recommended better training of apprentice welders about LEV use and positioning (Debia et al. 2014). Portable high-efficiency air filtration (PHEAF) can prevent construction dust migration to occupied spaces during building renovation. Using a photometer, Newcomer et al. (2018) found that some PHEAF filters do not provide adequate protection.

Several construction studies investigated high-velocity, low-volume LEV attached to hand tools, also known as shrouded tools. O’Brien et al. (1989) used a DRI to determine a 71% reduction in concentration when workers used a hand-held sander with a shroud. Keller and Chata (2018) tested LEV dust collectors on hand-held sanders and saws and classified different tools as high or low emitters. Croteau et al. (2004)
also found significant reductions in concentration with shrouded, ventilated tools during concrete grinding activities. Saidi et al. (2020) assessed and optimized different LEV including shrouds for simulated granite polishing. These studies validated an earlier study on the use of shrouded sanders used in other industries (Heitbrink et al. 1994). Garcia et al. (2014) linked DRI measurements to VEM to identify tasks or work practices that led to higher particle counts. They determined that an aftermarket LEV did not effectively reduce silica exposure while cutting roofing tiles with hand-held saws (Garcia et al. 2014).

Lead abatement by scraping or sanding lead-painted surfaces can expose construction workers and others to lead aerosols. Using DRI, Choe et al. (2000) monitored the decay of particle concentration by size and validated that the mandated times between abatement, cleaning, and clearance were adequate to allow dust to settle and be amenable to cleaning.

**Agricultural workplaces**

Agricultural dust control was investigated with DRIs by Peters et al. (2015). They evaluated shaker dust collectors in the lab and field and found that they effectively controlled dust in swine farrowing operations. Most agricultural evaluations involved tractors. Leaks in tractor cabs and pesticide application vehicle filtration systems have been identified and controls maintained using DRIs (Hall et al. 2002; Heitbrink et al. 2003). Some investigators recommended refinements in the American Society of Agricultural Engineers (ASAE) DRI method of testing these filtration systems (Heitbrink et al. 1998; Heitbrink and Collingwood 2005; Moyer et al. 2005). Heitbrink and Collingwood (2005) found that carbon brushes on cab ventilation blower motors were a source of submicron particles. Moyer et al. (2005) recommended using the size range 0.3–0.5 μm for performance specifications and the use of a dilutor if coincidence is an issue. They used smoke tubes and a DRI to identify leaks and tested cab air quality while the vehicle was stationary and mobile. An Australian study of farming operations on agricultural fields placed DRIs inside tractor cabs and showed higher particle counts during seeding operations compared to chemical spraying (Gilbey et al. 2018).

**Mining environments**

Mining workplaces have used various DRIs including a NIOSH-developed personal dust monitor (PDM) to assess exposure (Volkwein et al. 2002; Cecala et al. 2005; Page et al. 2008) The PDM is a tapered element oscillating microbalance personal monitor and provides miners with information to adjust their work activities and position relative to emissions to reduce dust exposure (Mischler et al. 2019). The supplemental filter in the PDM has been used to calibrate other area sampling DRIs to evaluate controls in a drilling operation (Cecala et al. 2005). Keeping the drill cab door closed, moving cab heaters to the ceiling, improving cab cleanliness, and using a sweeping compound to clean the cab floor reduced particle counts in the cab (Cecala et al. 2005). They noted a decrease in filter efficiency with time for the electrostatic filter media (Cecala et al. 2005). NIOSH researchers adapted a consensus standard method (ANSI/ASAE 2003) for testing agricultural machinery cabs’ filtration systems, to assess mining vehicle cabs (Organiscak et al. 2013). They used two DRIs to compare the end of shift inside relative to outside concentrations and identified damaged filters for replacement; they recommended this method for maintenance.

Vehicle emissions in a mine affect aerosol concentrations. Bugarski and Hummer (2020) assessed concentration reductions by different emission controls in different vehicle types building on earlier work done by this group (Bugarski et al. 2009). Bugarski et al. (2016) evaluated the effect of substituting hydrotreated vegetable oil renewal diesel fuel (HVORD) in different engine types. Compared to ultra-low sulfur diesel, the HVORD reduced the particle number concentration in a naturally aspirated engine but not in a turbocharged electronically controlled engine (Bugarski et al. 2016).

Another proactive strategy to reduce mining dust exposure is increasing the bite depth of drilling roof bolts as demonstrated using a DRI by Jiang et al. (2018). Seaman et al. (2018) used a cloud aerosol spectrophotometer with polarization DRI to determine optimal pressure and spray orientation to knockdown float coal dust; a DRI was needed to determine contemporaneous size distributions relative to the operating parameters of the control strategy. The study by Seaman et al. (2018) harkens back to one of the earliest reported uses of a DRI in British collieries; the Safety in Mines Scattered Light Instrument output showed that water is preferable to steam to suppress mining dust (Blackford and Harris 1978). Paluchamy et al. (2021) noted that DRIs can help investigators customize engineering solutions to reduce dust exposure in mines. Cecala et al. (2020) provide an excellent summary of engineering controls in mines and the International Council on Mining & Metals (2022)
effectively explains the benefits of using DRIs to improve mining conditions.

**Conventional manufacturing: Machining operations**

Metalworking fluid (MWF) mist reduction by enclosure, ventilation, and/or mist collectors has been studied in vehicle machining plants by many investigators (Yacher et al. 2000; Heitbrink et al. 2000a, 2000b; O’Brien 2003; Heitbrink et al. 2007; Sheehan and Hands 2007). Sheehan and Hands (2007) used DRIs to compare two identical production lines with two levels of LEV and showed complete enclosure cut mist concentrations in half. They also demonstrated an 80% reduction in the mist by shutting off MWF delivery during downtime and 87% effectiveness of improved enclosure on one specific operation. They recommended continued DRI monitoring to assess control integrity over time. Lillienberg et al. (2008) also noted the effectiveness of complete enclosure and showed that the use of compressed air increased concentrations. In addition to addressing the adequacy of mist collection (Yacher et al. 2000) and of LEV, DRIs helped Heitbrink et al. (2007) identify gas heating of recirculated air in the general ventilation system as a source of fine particles in the machining environment. O’Brien (2003) and Yacher et al. (2000) used DRIs to assess the effect of new MWF mist collectors. Based on their measurements with DRIs, Heitbrink et al. (2000a) explained that industrial hygienists need to reevaluate MWF mist control strategies if a process change results in higher tool speeds that generate more mist. In a more recent study, Wei et al. (2020) used a photometer to validate a computational fluid dynamics (CFD) model for a general ventilation design in a machining plant.

**Other conventional manufacturing operations**

Welling et al. (2009) used DRIs to assess wood dust particle number and size generated from sanding in a plywood production area and measured dust in the ventilation system. They conducted an additional lab chamber study using DRIs to measure filter efficiencies (Welling et al. 2009). Thorpe and Brown (1998) used a DRI to determine that the effectiveness of woodworking dust extractors was enhanced by vacuuming out the filter bag.

O’Brien et al. (1992) used VEM and one of the earliest optical particle counters (OPC) by Royco in a steel foundry to assess grinding tasks that affected exposure and determined the effectiveness of a downdraft hood. Pouring operations at a brass foundry provided NIOSH researchers with another early opportunity to use a DRI aligned with video. They found most operations were well controlled except for the transport of an unventilated full ladle of molten metal (Edmonds et al. 1993). Gressel (1997) used a DRI to evaluate an LEV system for a foundry casting-cleaning process and found a new downdraft hood worked effectively to reduce concentrations. He combined DRI with VEM to see which tasks generated significant dust (Gressel 1997). Choi and Lee (2022) found elevated particle counts when workers conducted maintenance on a scrubber used to control emissions in the semiconductor industry.

**Advanced manufacturing: Nanotechnology**

Advanced manufacturing includes innovative technologies to design and manufacture products and NIOSH has identified at least eight new technologies that can impact worker health (NIOSH 2021). Nanotechnology is one of these emerging technologies with the potential for aerosol exposure.

Several studies used DRIs to assess the control of nanoparticle emissions in research facilities, industrial workplaces, and aftermarket applications. These include determining how well LEV and general ventilation controlled the release of nanoparticles from aluminum surface treatment (Santos and Vieira 2017) and the effectiveness of LEV to reduce the concentration of engineered nanoparticles (Old and Methner 2008; Methner et al. 2012b; Thompson et al. 2013; Debia et al. 2016; Garcia et al. 2017). Cena and Peters (2011) determined that using a biosafety hood was effective in controlling respirable particles during the sanding of nanocomposite materials. Cesard et al. (2013) and Lo et al. (2015) also validated that a biosafety cabinet was effective for controlling nanoparticle emissions. Lo et al. (2012a, 2012b) studied carbon nanotubes and emphasized the importance of keeping enclosure doors closed and that some biosafety cabinets need supplemental ventilation. Dunn et al. (2014) used DRIs and an inexpensive particle generator commonly used in respirator fit testing; they generated tracer nanoparticles to determine the effectiveness of and source of leaks in a hood as well as the impact of a supply air diffuser. They recommended a combination of tracer aerosol and tracer gas as a sensitive approach for assessing hood design and operation (Dunn et al. 2014). Vosburgh et al. (2011) found that a canopy hood provided inadequate control of nanoparticles in a seam sealing process at a polytetrafluoroethylene apparel factory.

Heitbrink et al. (2015) determined that a process change could reduce emissions until more permanent
Additive manufacturing: Three-dimensional printing

Additive manufacturing (AM) is another emerging technology presenting potential aerosol exposure risks. It has evolved from being a method for rapid prototyping of a new product to being incorporated into production processes in industry and university maker spaces, libraries, and residences (Kellens et al. 2017). Three-dimensional (3-D) printing is the common term although some techniques such as powder bed processes using fusion or sintering to produce metal products have different challenges compared to typical 3-D printing using plastic filament (Walter et al. 2018).

DRIs have been used to determine emissions and estimate exposures and Chen et al. (2020) provide an excellent measurement approach. Roth et al. (2019) state that although it is a different type of advanced manufacturing, the challenges of AM parallel nanotechnology are because AM is being incorporated into systems using old and new technology and being applied in atypical environments such as consumer sites.

Dunn and colleagues (2020) at NIOSH have developed and tested an engineering control for 3-D printers; the device has an extruder head capture hood providing cooling air in one direction and capturing emissions via an exhaust. Their device showed a 98% reduction in the ultrafine particle emission and they replicated this success when using a DRI to measure ultrafines with and without the control in a simulated makerspace containing 20 3-D printers. The NIOSH investigators also found that the room volume and greater general ventilation enhanced removal in the makerspace.

Bau et al. (2020) investigated a direct energy deposition AM process conducted within a sealed, vented enclosure using DRIs placed at the source, near-field, far-field, and on the operator. They assessed number concentration and size distributions and used a dilutor and four-way flow splitter for simultaneous real-time readings. They found a particle concentration spike occurs when the operator opens the door to remove a part from the enclosure. They assessed and recommended an 8-min time delay before opening thus allowing the ventilated enclosure to reduce concentrations to a tenth of the production concentration. Kim et al. (2021) found that nanoparticles were substantially reduced when a printer was enclosed vs. open. Kwon et al. (2017) and Zontek et al. (2017) also found that ventilated enclosures with HEPA filtration provided effective control with a 99% reduction. Gu et al. (2019) found that a filtered printer cover reduced concentrations by 94%. Keeping the enclosure door closed with interlocks (Jensen et al. 2020; Ipiña et al. 2021) and having a ventilated enclosure with filtration are very effective particle reduction strategies (Kwon et al. 2017; Zontek et al. 2017; Stefaniak et al. 2019; Katz et al. 2020; Ipiña et al. 2021; Viitanen et al. 2021). Yi et al. (2016) and Kwon et al. (2017) note that most 3-D printers do not come with these features and Viitanen et al. (2021) warn about heat buildup in the enclosure. Yi et al. (2016) suggest using a ratio of the particle metric (number, etc.) divided by the mass of filament consumed or the mass of printed object to compare conditions.

Zontek et al. (2017) in their enclosure study compared two workplaces, a well-ventilated lab and a poorly ventilated one. The poorly ventilated lab mimicked what would be expected in residential or other non-industrial settings. Room concentrations rose but were localized around the printer in the well-
ventilated room and distributed throughout the poorly ventilated one. Saliakas et al. (2022) tested room air cleaners and noted that unless properly positioned they can draw particles out of a 3-D printer enclosure.

Pre and post-processing of parts can produce aerosol exposures along with the production phase of AM and require effective ventilation (Väisänen et al. 2019; Runström Eden et al. 2022). Using DRI, Runström Eden et al. (2022) compared four facilities using different printing methods and ventilation. They noted that due to LEV, mechanical general ventilation, and the use of glove boxes, the particle counts were low but explained that post-production sanding and related tasks generated the highest concentrations and involved the most time of potential exposure. Väisänen et al. (2019) in their comparison of different AM types also found that post-processing generated the most particles and that processes involving solid materials as the feedstock generated more particles. In addition to production, pre- and post-processing exposures need to be assessed and appropriate engineering controls applied.

Non-industrial sites

Instructors at a U.S. Air Force small arms firing range were fitted with wearable DRIs and stationary DRIs were positioned behind the ready line (Grabinski et al. 2017). The devices were able to distinguish differences in aerosol size distributions generated by different weapons and determined that the ventilation system could not control peak emissions (Grabinski et al. 2017).

Various procedures in hospitals generate aerosols including construction and laser surgery. Lee et al. (2018) used DRIs to assess surgical smoke generated by a mockup surgery in an operating room. They compared concentrations without LEV versus an LEV wall irrigation suction unit with filtration versus an LEV with a smoke evacuation system (Lee et al. 2018). Although both LEV systems reduced concentrations, the smoke evacuation system was the more effective option (Lee et al. 2018). LEV-like vented face shields (Esteban Florez et al. 2021) and high-volume evacuators have been shown to reduce aerosols in dentistry (Jacks 2002; Choudhary et al. 2021; Blackley et al. 2022; D’Antonio et al. 2022; Fennelly et al. 2022; He et al. 2022).

Offices and residential aerosols have been evaluated with DRIs. A portable air cleaner in an office was evaluated by Stauffer et al. (2020) to determine how well it removed wildfire PM$_{2.5}$ aerosols, a growing problem in the western U.S. The air cleaner removed 73% of aerosols during working hours and 92% during off hours. They recommended using air cleaners because simply staying indoors does not adequately protect people from wildfire smoke. Dal Porto et al. (2022) compared a time of flight DRI and a low-cost sensor to test a Corsi Rosenthal box (a homemade air cleaner) and found that the sensor provided a good estimate of the clean air delivery rate (CADR), a metric determining the effectiveness of room air cleaners. DuBois et al. (2022) tested the position of air cleaners in an office and noted that positioning the cleaner 12 in. from the breathing zone provided optimal, albeit not practical control.

Vacuum cleaners serve as a control of dust in residences and offices. Willeke et al. (2001) developed a method using an OPC and probe to assess the efficiency of individual components of a vacuum cleaner. Trakumas et al. (2001) used this method to test different vacuum cleaner collection methods and determined the efficiency of the primary collector (e.g., filter) and the amount of re-entrainment due to filter loading or re-aerosolization in wet collectors. Reponen et al. (2002) from that same laboratory, assessed the vacuum cleaners’ built-in dirt sensors and pickup efficiencies.

Martin et al. (2006) used paired OPCs to determine the effectiveness of a filtration system at a U.S. Post Office facility. They used a modification of the agricultural cab method and found the method was useful for assessing filtration systems. However, aerosol DRIs are not always the most effective method for assessing controls even in similar worksites. Beamer et al. (2004) found that high background paper aerosol interfered with their DRI aerosol sampling method for assessing the adequacy of LEV for mail sorting equipment. They could not accurately assess the LEV using DRIs and recommended not using aerosol testing for assessing these postal machines and instead preferred gas tracer decay methods.

Some investigators have used DRIs to identify specific types or components of ventilation systems or other controls. Lo et al. (2017) focused on a specific type of LEV, the down-flow booth which is found in various industries. Using multiple DRIs, they measured a surrogate aerosol, lactose, inside the working area of the booth and outside (Lo et al. 2017). They measured the effect of the booth size, supply air velocity, location of the work, and the use of vinyl curtains and determined that down-flow booths are an excellent control measure when used as they recommended. Moyer et al. (2007) adapted and scaled up a method for agricultural cabs (ANSI/ASAE 2003) to
Table 1. Most common DRIs used to evaluate controls.

| DRI Type | Size range (um) | Measures | Challenges/ Limitations | Solutions | Application | Examples of field studies using the device (Category 2) |
|----------|-----------------|----------|-------------------------|-----------|-------------|-----------------------------------------------------|
| OPC      | 0.25 to 26      | Particle # & optical diameter; particle # in specific size ranges | Refractive index & shape concerns; coincidence | Calibrate to specific aerosol using integrative sampling; dilutor (e.g., Organiscak et al. 2013) | Used in all workplace categories to assess aerosol generating processes producing a wide range of sizes; ANSI/ASAE method for tractor cabs; NIOSH neat method for nanoparticles; some room air cleaner methods (e.g., Vit et al. 2020) | Choe et al. 2000 (C); Heitbrink and Collingwood 2005 (A); Organiscak et al. 2013 (M); Yacher et al. 2000 (Ma); O’Brien et al. 1992 (O); Cena and Peters 2011 (N); Runström Eden et al. 2022 (Ad); Trakumas et al. 2001 (NI) |
| CPC      | 0.01 to slightly greater than 1.0 | Total particle # <1.0 um | Coincidence if >100,000 p/cc | Dilutor (e.g., Evans et al. 2008; Vosburgh et al. 2011) | Used to assess ultrafine and nanoparticles; frequently used in advanced manufacturing sites; NIOSH neat method for nanoparticles | Methner et al. 2012a (N); Eastlake et al. 2016 (N); Old and Methner 2008 (N); Runström Eden et al. 2022 (Ad); Martin et al. 2017 (N) |
| SMPS     | 0.01 to 0.80    | # Concentration; electric mobility size | Very expensive; heavy; most not field rugged | Use a cart in workplace | Used to size ultrafine and nanoparticles; usually lab based studies (e.g., Dunn et al. 2020; Saidi et al. 2020); used to assess generated aerosol (e.g., Welling et al. 2009; Cesard et al. 2013; Dunn et al. 2014); may discern individual nanoparticles vs. Agglomerates (Santos and Vieira 2017) | Heitbrink et al. 2015 (N); Lee et al. 2018 (O); Grabisinski et al. 2017 (O); Bau et al. 2020 (Ad); Thompson et al. 2013 (N); Bugarski and Hummer 2020 (M) |
| Photo-meter | Slightly less than 1 to greater than 10 | Mass concentration & mass concentration in size ranges | Refractive index, shape and relative humidity concerns | Calibrate to specific aerosol using integrative sampling at specific site | Used in all workplace categories with processes generating micrometer size aerosol; used to compare to integrated sampling (e.g., Croteau et al. 2004); common in conventional manufacturing studies; used to identify post processing problem in additive manufacturing (Runström Eden et al. 2022) | Heitbrink et al. 1994 (C); Garcia et al. 2014 (C); Gilbey et al. 2018 (A); Sheehan and Hands 2007 (Ma) |
assess filter-bank systems and determine change-out schedules. Before field testing, they calibrated identical devices as paired units with correction factors to minimize bias and placed one upstream and one downstream of the filter bank to determine total efficiency. Raynor and Chae (2004) field-tested polyolefin versus glass fiber filters using DRIs and indicated that the beneficial effect of the electrical charges on the polyolefin decreases with time and dust loading. Liang et al. (2022) used an OPC to show that pre-misting enhances aerosol scavenging of a wider size range of particles when using spray methods to knock down dust.

**Techniques and methods for evaluating controls with DRIs**

DRIs allow occupational health and safety professionals to intervene when controls are failing or ineffective (International Council on Mining & Metals 2022). For control evaluations, investigators have used diverse types of instruments and have had different strategies (personal vs. area sampling and lab vs. field studies). Table 1 summarizes the most commonly used instruments and Supplemental Table 1 provides information about the categories of DRIs and the specific strategies authors used to conduct assessments. For evaluation of controls, field studies using area samplers/sampling are the most common as shown in Supplemental Table 1. The NIOSH NEAT method recommends using a combination of integrated sampling and three DRI samplers (CNC, OPC, photometer) to assess nanoparticle emissions and the effectiveness of controls (Methner et al. 2010a, 2010b; 2012a, 2012b; Brenner et al. 2016; Eastlake et al. 2016; McGarry et al. 2016; Garcia et al. 2017) and this strategy could be applied to other situations. A multi-metric DRI approach requires alignment of the instruments’ sampling time intervals so datasets can be compared (McGarry et al. 2013). The selection of an instrument or combination of instruments depends on the aerosol size characteristics and limitations of the instrument as noted in Table 1.

One can compare DRI output with and without the control of individual tasks, devices, or systems (e.g., O’Brien et al. 1992; Sheehan and Hands 2007; Vosburgh et al. 2011; Lee et al. 2018; West et al. 2019) or assess whether existing controls are adequate without comparing to a “no control” metric (e.g., Edmonds et al. 1993; Miller et al. 2010). A good practice to average out any biases is to rotate two identical DRIs (control vs. no control or inside controlled space vs outside) (Cecala et al. 2005; Organiscak et al. 2013). In some situations, using one instrument alternated repeatedly “with” and “without” can account for any instrument drift (e.g., Vosburgh et al. 2011; Peters et al. 2015). Some investigators have used area sampling at the worker’s breathing zone, at the source, near-field, far-field (sometimes used as background), or a combination of these sites (e.g., Vosburgh et al. 2011; Brenner et al. 2016; Eastlake et al. 2016; McGarry et al. 2016; Bau et al. 2020; Hedmer et al. 2022). Determining background concentrations when processes are not operating is ideal but sometimes challenging in the field (Cena and Peters 2011; Brenner et al. 2016; Debia et al. 2016; Cooper et al. 2017; Martin et al. 2017). D’Arcy et al. (2016) measured outdoor air upwind of the facility as background.

### Table 1. Continued.

| DRI Type | Size range (um) | Measures | Challenges/ Limitations | Solutions | Application | Examples of field studies using the device (Category 2) |
|----------|-----------------|----------|-------------------------|-----------|-------------|-----------------------------------------------------|
| Time of Flight | 0.4 to 20 | Aero-dynamic size | Very expensive; heavy; most not field rugged | Use a cart in workplace; use in lab & substitute with field DRI (e.g., Peters et al. 2015) | Used with SMPS for particle size distribution over a wide range (Lo et al. 2015); help discern engineered nanoparticles from background (Thompson et al. 2013); ANSI/ AHAM method for room air cleaners (ANSI/ AHAM 2015) | Heitbrink et al. 2000a (Ma); Heitbrink et al. 2000b (Ma); Welling et al. 2009 (O); Lee et al. 2018 (O) |

1OPC = optical particle counter; CPC = condensation particle counter; SMPS = scanning electrical mobility or other electrical mobility particle sizer.
2C = construction; A = Agriculture; M = Mining; Ma = Machining; O = Other; N = Nanotechnology; Ad = Additive Manufacturing; NI = non-industrial
Dunn et al. 2014 reduced background concentrations with a room air cleaner to allow for better discrimination from the source while Heitbrink and Collingwood (2005) recommended using a high concentration of test aerosol (for example, incense) outside of the cab so the effect of the motor aerosol did not impact the interpretation of the adequacy of the cab filtration system.

Using the background concentrations, Heitbrink et al. (2015) described the process values vs. background, and others compared the mean of the process vs. background (Cena and Peters 2011; Lee et al. 2018). Some investigators have subtracted the average of before and after-process background values from the process concentrations (Old and Methner 2008; D’Arcy et al. 2016; Cooper et al. 2017). NEAT 1.0 used this method (Methner et al. 2012a) while NEAT 2.0 uses an integration of the DRI data from the full sampling period at a site away from the process (far-field) and does not subtract from the process values (Eastlake et al. 2016). Ramachandran et al. 2011 provide a fine explanation of why background subtraction is not always advised. McGarry et al. (2013) state that a process concentration metric of three or more times background concentration indicates the need for better controls in nanotechnology workplaces (McGarry et al. 2013).

Some standard methods for evaluating engineering controls have been developed using DRIs. An earlier version of ANSI-ASAE (2003) for testing agricultural cabs was improved by Heitbrink and his colleagues (1998) and the 2003 version was enhanced by Heitbrink and Collingwood (2005). The earlier and current methods use an OPC that measures particles in the size range of 2 to 4 μm and has a coincidence error of less than 5% (ANSI/ASAE 2003). Yit et al. (2020) reviewed three current air filtration test methods by ASHRAE, ISO, and the European Union and each of these uses a size-selective OPC and designates the size bins the DRI must have. Consumers Union conducts research on consumer products but they do not publish the specific test method; they use a particle counter to test room air purifiers (Santanachote 2020). In a review of home air cleaners, Shaughnessy and Sextro (2006) described and critiqued assessment methods including an earlier version of the current American National Standards Institute (ANSI)/ Association of Home Appliance Manufacturers (AHAM) protocol (ANSI/AHAM 2015). It employs DRIs to measure particle concentration decay to generate a Clean Air Delivery Rate (CADR). This method is cited by the EPA and American Lung Association as an appropriate metric but the authors warn that the size of the dust must be considered in interpreting and applying the results and that source control is always preferable to air cleaning (Shaughnessy and Sextro 2006). Ginetet (2012) offered an improvement on this method for lower concentrations.

**Aerosol concentration mapping**

Concentration mapping is a type of hazard mapping and is an effective visual representation of the spatial variability of an aerosol or any other quantifiable workplace hazard; when the hazard is an aerosol, the term aerosol concentration mapping (ACM) is used (Ramachandran et al. 2011). Industrial hygienists have used workplace diagrams to map sampling locations for decades (Vaughan et al. 1990; Martin et al. 2017). DRIs provide a powerful tool for mobile monitoring yielding large datasets that can be manipulated to produce surface maps that estimate concentrations at unsampled locations (Koehler and Peters 2013). Systematic measurements are taken in a grid pattern in the workplace. The instrument output can be downloaded into spreadsheets to make simple contour maps without sophisticated interpolation (O’Brien 2003; Sheehan and Hands 2007) or with more specialized mapping software, values can be interpolated to construct a more detailed map (Peters et al. 2006, 2012; Evans et al. 2008; Vosburgh et al. 2011; Koehler and Peters 2013). Although ACM with a DRI cannot replace personal sampling and is labor-intensive, it is an exploratory tool that refines our understanding of the workplace by providing a more comprehensive and comprehensible picture of a site. (O’Brien 2003; Evans et al. 2008; Park et al. 2010; Ramachandran et al. 2011).

**Uses of ACM**

As detailed in Supplemental Table 1, a variety of DRIs have been used for mapping and almost exclusively, area samplers/sampling has been used to generate maps. Different aerosols (nanoparticles, MWF mist, agricultural dust, combustion products, etc.) in various worksites have been investigated using mapping techniques. ACM with a DRI has been used to evaluate the effectiveness of controls (O’Brien 2003; Heitbrink et al. 2007; Sheehan and Hands 2007; Old and Methner 2008; Liu and Hammond 2010; Vosburgh et al. 2011; Reeve et al. 2013) and identify process sources (Dasch et al. 2005; Vosburgh et al. 2011; D’Arcy et al. 2016). Mapping can prioritize
potential sites (Dasch et al. 2005) and tasks (Vosburgh et al. 2011) for long-term personal aerosol sampling and inform the selection of similar exposure groups (Ramachandran et al. 2011; Vosburgh et al. 2011). Evans et al. (2008) and Kim et al. (2013) assessed the migration of ultrafine particles away from the source and others have identified non-process sources of ultrafine particles (Peters et al. 2006; Heitbrink et al. 2007). O’Brien (2003) showed a possible dose/response relationship by mapping MWF mist, defining areas of low, medium, or high exposure, and determining a spatial “pseudo” attack rate for hypersensitivity pneumonitis. Park et al. (2010) noted that ACM with DRIs can help plan more intensive sampling efforts by determining if sampling filters could become overloaded or concentrations are within instrument operating ranges.

**Techniques and methods for ACM**

**Measurement locations**

ACM endeavors, like any other sampling campaign, need to be well planned to produce a useful result. Selecting sampling locations is an initial step. Sampling locations have been selected using identifiable facility landmarks such as building support columns (O’Brien 2003; Peters et al. 2006; Sheehan and Hands 2007; Liu and Hammond 2010; D’Arcy et al. 2016) or defined, labeled spacing based on sampling duration and the overall size of the sampling area (Park et al. 2010). Recent developments such as indoor positioning systems using Bluetooth low-energy beacons (BLE), WiFi, ultrasound sensors, or light-based positioning (Qi and Liu 2017; Li et al. 2018; Molina et al. 2018) may be adopted by more workplaces and provide an opportunity for investigators mapping in the future. Ando et al. (2021) note that Wi-Fi round trip time (WiFi RTT) is more accurate than Bluetooth or other WiFi; they used this system, a smartphone, and DRI to map concentrations. The extent of the spatial resolution (locations/m²) can produce a coarser or finer sampling grid and examples are noted in Table 2 of Koehler et al. (2017). Most aerosol mappers use equidistant grids for ease of sampling; however, according to Koehler and Peters (2013), this method makes interpolation more challenging. To improve the assessment of sources, they recommend using an irregular sampling pattern with a finer grid close to sources and less resolution away from sources to improve accuracy instead of increasing the number of sampling locations throughout the workplace (Koehler and Peters 2013; Koehler et al. 2017).

**Moving DRI versus sensor network**

A map can be created from one or more DRIs that are moved from one sampling location to another or with a sensor network. The advantage of moving a single DRI is that less equipment can mean a lower capital investment. However, differences in temporal variability versus spatial variability may be an issue. Specifics regarding both options are outlined below.

When moving instruments from sampling location to sampling location, investigators can use an individual instrument (O’Brien 2003; Sheehan and Hands 2007) or use a cart to hold multiple co-located instruments that need to be synchronized for simultaneous data collection (Peters et al. 2006; Heitbrink et al. 2007; Park et al. 2010; Vosburgh et al. 2011; Berman et al. 2018). Although not conducting true personal breathing zone measurements, some investigators placed the instrument inlet at breathing zone height (Peters et al. 2012) and, in some cases, right near an actual worker’s breathing zone (Vosburgh et al. 2011).

The time to measure one sample at one location is the sampling interval and a 1-min sample rate was commonly used (Peters et al. 2006; Heitbrink et al. 2007; Liu and Hammond 2010; Park et al. 2010; Kim et al. 2013). Sampling should be avoided during breaks and just after the resumption of a process; steady-state working conditions are recommended (Sheehan and Hands 2007; Liu and Hammond 2010). Aerosol sources that have unpredictable, unstable emissions are more challenging to accurately map (Koehler and Volckens 2011). To reduce temporal variability, Koehler et al. (2017) recommended completing the overall sampling duration as quickly as possible and some have limited sampling episodes to about 2 hr (Peters et al. 2006; Park et al. 2010).

Temporal variability is a major issue with ACM and sometimes temporal variability is mistakenly interpreted as spatial variability (Zuidema et al. 2019a). Both result in autocorrelation problems that challenge statistical interpretation; (Koehler and Peters 2013). The key, like any other sampling, is to conduct replicate sampling (Koehler et al. 2017). Repeated sampling has been conducted within 1 d (Kim et al. 2013; D’Arcy et al. 2016), on sequential days (Dasch et al. 2005), monthly (Sheehan and Hands 2007), or seasonally (Peters et al. 2006, 2012; Heitbrink et al. 2007; Evans et al. 2008; Berman et al. 2018). Reeve et al. (2013) sampled three times per day for five randomly chosen winter days.
Sometimes, the temporal variability is different for contemporaneously sampled metrics, for example, Peters et al. (2006) found that the day-to-day temporal variability was greater for larger particles than ultrafine particles and consequently greater for mass concentration than number concentration. One can estimate the temporal variability for a source using the coefficient of variation (CV) of replicate samples (Koehler et al. 2017). Using the CV of the source with the highest temporal variability, Koehler et al. (2017) laid out a flow diagram of a method to address the temporal variability issue.

Moving an instrument throughout the workplace is a grab sample technique that cannot fully account for temporal variation even with multiple measurements. Peters et al. (2012) used a combination of mobile and stationary monitors to determine if the less labor-intensive stationary setup could be used for effective monitoring. One DRI in a stationary location can measure temporal change assuming that the location is representative and a mobile cart with a second DRI can be employed to determine the spatial differences. The mobile DRI’s output can be modified based on the stationary DRI. Liu and Hammond (2010) also used a combination of stationary monitors to evaluate temporal changes and typical mapping protocols for spatial assessment.

Another way some have addressed temporal variability in ACM is a stationary sensor network using many low-cost sensors (Berman et al. 2018; Zuidema et al. 2019a; Goede et al. 2021). Due to the limitations of current low-cost sensors, these devices may produce less accurate maps than mobile DRIs; however, the resulting multiple maps can be compiled as a time series into a video to see temporal and spatial trends (Zuidema et al. 2019a). Many sensor designs are similar to photometers and their signal is converted after calibration to a particle mass concentration (Zuidema et al. 2019b). Any photometer’s reading is affected by refractive index, particle chemistry, and size (Zuidema et al. 2019b) and they describe how to minimize errors in a sensor network by using co-located graviometrically calibrated traditional photometers and developing weekly correction factors (CFs). Zuidema et al. (2019b) found that CFs generated using stationary DRIs were different from process-specific CFs, and recommended the use of process-specific CFs. Whether using low-cost sensors or more expensive stationary DRI to assess temporal variability, the location and number of instruments need to be optimized (Reeve et al. 2013; Zuidema et al. 2019b).

Creating the map

In addition to improvements in DRI technology and interfaces, one of the most important improvements in ACM is the incorporation of established geospatial techniques and mapping software for interpolating concentrations (Koehler and Peters 2013). Although there are other methods, an appropriate common interpolation method for ACM is kriging (Koehler and Peters 2013). Kriging optimizes interpolation by weighting the neighboring data points and provides an unbiased prediction of the un-sampled sites based on mathematical models (Koehler and Peters 2013). Proximal points are given more weight than those at a distance because nearby sites should be more similar to each other than those more remote (Koehler and Volckens 2011; Koehler and Peters 2013). Kriging quantifies the prediction variability; a low kriging variance indicates a high prediction precision and to obtain a low kriging variance one needs closer sampling points (Berman et al. 2018). Koehler and Peters (2013) and Ellis et al. (2022) provide more detail about the limits, challenges, and importance of interpolation in concentration mapping.

Maps must be intelligible and unambiguous to be a powerful visual aid for an audience. Industrial hygienists use ACM to convey information to management and workers about the sources and severity of the aerosol risk and to convince them to adopt recommended remedies. ACM usually represents quantitative data with areas of high and low concentrations. As such, a sequential color scheme should be used, where light colors are used for low concentrations stepping up in gradations to darker colors for higher concentrations (Harrower and Brewer 2003). Generally, it is easiest to achieve this by using a color scheme that uses one hue, for example, shades of blue from light to dark (e.g., Peters et al. 2012). Color schemes that do not imply order, such as a rainbow or random color hues which are appropriate for qualitative data, or that restrict comprehension by people who have color vision impairments should be avoided (Harrower and Brewer 2003). ColorBrewer2.org (Brewer and Harrower 2021) is a free, online interactive tool that provides color schemes for mapping and data visualization.

Industrial hygiene decision-making concerning workplace aerosols is aided by ACM. As with any other exposure metric, if aerosol concentrations are underestimated or overestimated, poor decisions may be made regarding control strategies, wasting money, or more importantly, putting workers at risk (Koehler et al. 2017). Selecting appropriate calibrated DRI,
choosing fine grids close to sources, using brief sampling campaigns, replicating measurements, assessing temporal variability, interpolating appropriately by using mapping programs, and conveying the data properly can provide excellent aerosol maps that lead to good decision-making.

**Video exposure monitoring**

Video exposure monitoring (VEM) is a powerful application of DRIs that can assist with better characterizations of workplace aerosol exposures. 80-90% of exposure limit exceedances can occur in only 10–20% of the job (McGlothlin 2009). VEM can focus on the peak exposures driving up TWA and/or causing sensitization (Gummesson et al. 2015). By synchronizing real-time or near real-time exposures with a video recording of workers and/or their related work environment, VEM allows the visualization of aerosol exposures and emissions along with the actions that influence them. VEM can assist with research, emission source identification, task analysis, training, and risk communication and it can stimulate worker participation (Rosén et al. 2005). A VEM system consists of the DRI, video recording equipment, and computer software/hardware that combines and analyzes the exposure data.

The merits of VEM have been appreciated since the mid-1980s by NIOSH in the U.S. (Gressel et al. 1985) and similar governmental health and safety agencies in Sweden, the U.K., and other European nations (Rosén and Lundström 1987; Rosén et al. 2005). However, because VEM focuses on short-term exposures that are not part of the regulatory framework it does not get the attention it deserves (McGlothlin 2005, 2009; Gummesson et al. 2015). Despite NIOSH researchers having published numerous studies using VEM, the technology is not an established, well-publicized NIOSH method (McGlothlin 2005, 2009; Gummesson et al. 2015).

NIOSH researchers adapted the videography being used for ergonomic assessment to the evaluation of aerosols and used the term video exposure monitoring (Gressel et al. 1985; 1987; McGlothlin 2005; Cecala et al. 2020). Swedish scientists developed PIMEX (Picture Mix and Exposure) (Rosén et al. 2005). The UK’s Health and Safety Executive’s (HSE) also developed a version, Exposure Level Visualization (ELVis) (Rosén et al. 2005; Walsh et al. 2009). Due to the work of researchers in these countries, simple worker activity videos with bar graph overlays evolved into systems with interactive graphics, real-time playback, averaging, threshold sets, bookmarking, and other features (Rosén et al. 2005; Haas et al. 2018).

In 1992, NIOSH established VEM methodology and statistical interpretation (Gressel et al. 1992). Over decades, technology for video monitoring changed from large camcorders to smaller handheld cameras (Rosén et al. 2005; Walsh et al. 2009). Smaller aerosol monitors with expanded functions allow data to be transmitted wirelessly between the DRI and computer via two-way radio telemetry or data can be stored in the instrument and downloaded to a computer (Rosén et al. 2005). The area and personal aerosol monitoring data have been combined with stationary video monitoring by an observer (Echt et al. 2002; Vosburgh et al. 2011), but smaller cameras now allow the workplace to be seen from the worker’s point of view (Cecala et al. 2013; Reed et al. 2014).

Today, commercial, generic video overlay devices are available that can merge video with data from any device that can output comma-separated values (csv); these devices cost ~$1,800 (VideoLogix 2021). An easy-to-use software called EVADE (Enhanced Video Analysis of Dust Exposure) is available for free download from NIOSH (Cecala et al. 2014). Many investigators from around the world have used EVADE (Cecala et al. 2020). EVADE was developed by the NIOSH Office of Mine Safety and Health Research Computational Research Team in Pittsburgh to use with their Helmet-CAM system (Cecala et al. 2013; Reed et al. 2014; Haas and Cecala 2015; Patts et al. 2020). This system overcomes the limitations of stationary cameras because the Helmet-CAM is on the worker and despite its name, the camera is usually attached to the strap of the backpack that contains the DRI (Cecala et al. 2013, 2020).

**Applications of VEM**

**Task identification and exposure determinants**

Initial efforts simply used video to identify tasks that appeared to increase aerosol levels and to evaluate these statistically (Gressel et al. 1987). An early study using video to supplement direct reading output found that the depth of scooping into a bag was the critical step influencing dust exposure during the weighing and transferring of powders (Gressel et al. 1987; 1988). These same authors investigated automotive brake servicing and VEM corroborated that using an air-driven impact wrench was a major source of aerosol exposure (Gressel et al. 1988). Yacher et al. (2000) used VEM and an aerosol photometer to assess the tasks that exposed workers to high particulate
levels in a machining plant. They identified working inside a machining center and opening doors of partially enclosed machining centers as opportunities for exposure. Using PIMEX VEM and a DRI, Skauget et al. (2014) showed that the anode skirt changeout in a Söderberg pot room generated high emissions of aerosols. Scheeper et al. (1995) evaluated woodworking tasks with PIMEX while Walter et al. (2018) used it to evaluate additive manufacturing. Using VEM, Garcia et al. (2014) identified tile cutting and tile cleaning as the main contributors to respirable dust exposure in a study of roofer. The ELVis was used by Walsh et al. (2009) to compare tasks in two different environments, a poultry barn, and a pharmaceutical process, demonstrating its effectiveness in a high dust concentration, low light situation vs. a well-lit clean operation. Earlier work in the U.K. investigated critical aerosol-generating tasks in commercial bakeries, woodworking, and quarries (Gray et al. 1992; Unwin et al. 1993). The NIOSH EVADE system showed that actions such as shaking dirty clothing, not using existing fans, and using cloth seats in vehicles elevated dust exposure levels for miners (Haas and Cecala 2015). Parker et al. (2022) used EVADE to link data from a DRI and an ultra-wideband position tracking system and found that military firing range instructors had their highest exposure when they helped their students at the firing line.

VEM allows for the assessment of exposure determinants including exposure time. The task analysis power of this method was effectively shown by Douwes et al. (2017). They identified 23 different tasks for joiners and 7 tasks for furniture makers, provided the percent of time allocated to the task, and determined exposure ratios for the tasks. In a study of pouring operations in a foundry, tasks were assessed to determine average concentrations, cumulative time, and cumulative exposure (Edmonds et al. 1993). Moving an unventilated full ladle accounted for greater than a third of the exposure although only 10% of the total time (Edmonds et al. 1993). Thrarr and Zimmer (1997) used VEM to qualitatively assess what activities in rock drilling cause or reduce aerosol exposure and were able to determine why area samples were different from personal samples. For example, one drilling rig operator positioned himself upwind at his control console spending almost half his time there (reducing his exposure) while another spent over a third of his time with his cab window open thus increasing his exposure (Thrarr and Zimmer 1997). VEM can, therefore, identify how dust exposure during outdoor work is influenced by wind-produced natural ventilation (Mazzuckelli et al. 2004) and worker position relative to the wind (Thrarr and Zimmer 1997; Echt et al. 2002).

As noted, VEM can also be used to code tasks for statistical comparisons. Vosburgh et al. (2011) used VEM to code tasks and their duration to assign workers to groups in an apparel manufacturing facility and compared the groups in terms of exposure to nanoparticles. In a variant of VEM, time-lapse images were generated from a GoPro camera worn by workers to define distinct activities and duration to predict which tasks would have the highest PM$_{2.5}$ concentrations (Laskaris et al. 2019). This type of task analysis was deemed more accurate than worker self-reported activities (Laskaris et al. 2019).

**Assisting control assessments**

Gummesson et al. (2015) provided a powerful methodology for determining what tasks to control and VEM can aid in this endeavor. EVADE and similar software allows the bookmarking of excessive exposures to highlight the actions or sources that are important to control. For example, in a casting process, using video to interpret DRI output identified pouring and shakeout as needing additional controls (Gressel et al. 1988). In two other casting investigations, an assessment of a downdraft hood and casting cleaning tools was assisted by using VEM (O’Brien et al. 1992; Gressel 1997). In an evaluation of dust emission control from mortar removal, the ventilation was shown to be inadequate when the gap between the mortar and the shrouded tool exhaust was too large thus better LEV and improved training were needed (Collingwood and Heitbrink 2007). Douwes et al. (2017) evaluated control strategies of LEV on a tool, a downdraft table, and extraction to a bag and found that these techniques were more successful in the laboratory than in the field. VEM can also show when controls work, such as a study demonstrating the effectiveness of a ventilation system to control dust from slate splitting (Walsh et al. 2000).

VEM can hone engineering controls and sometimes determine quick solutions (Gummesson et al. 2015; Haas and Cecala 2017). One mining study using EVADE demonstrated that simple fixes such as covering breakroom seats and kneeling pads with vinyl, cleaning vehicle cabs, using leather gloves, and providing clothes-cleaning booths reduced dust exposure (Haas and Cecala 2017). Another study noted that in addition to protecting workers, using VEM to manage controls could enhance product quality in pharmaceuticals (McGovern 2004).
VEM can be a powerful aerosol control management and planning tool. NIOSH investigators analyzed aggregated DRI respirable dust exposures and video datasets using EVADE to prioritize controls and improve work practices (Patts et al. 2020). They focused on exposures that were greater than ten times the mean worker exposure to determine, mathematically, if reducing these values would decrease the worker’s average exposure by at least 20% (Patts et al. 2020).

**Improved risk communication and training**

The ability to see video and the corresponding data immediately is useful for everyone involved in the workplace (Rosén et al. 2005). VEM allows for work practices and exposures to be observed by the worker so they can see what actions influence their exposure (Kuhl and Dobernowsky 2011; Reed et al. 2014) so the worker can become invested in changing actions to reduce exposure (Hedlund et al. 2015). A study of welders indicated that after seeing the VEM output, the welders were motivated to help develop preventative measures and continued to properly position themselves and their extraction systems to minimize exposure (Kuhl and Dobernowsky 2011). Working with EVADE, thresholds can be indicated and high concentrations bookmarked for easy playback in safety meetings (Cecala et al. 2013; Reed et al. 2014).

A participatory, iterative process to control exposures using PIMEX has proven successful in other countries (Rosén et al. 2005; Rosén and Andersson 2009). Many control methods require maintenance and correct use of controls by the worker; VEM helped motivate workers by showing conditions before and after improvements were made (Rosén and Andersson 2009). Managers used Helmet-CAM to ascertain problems, communicate with workers about solving the problems, and assess whether the action reduced dust levels (Haas et al. 2016b). Helmet-CAM provided opportunities for management and workers to discuss and evaluate minor changes that yielded reductions in silica exposure (Haas and Cecala 2017). Being able to use EVADE interactively increased worker awareness, prompted questions, and made them more engaged in control strategies (Haas et al. 2016a). Videos can generate productive discussions to help solve specific exposure situations and overcome language or cultural barriers (Rosén et al. 2005).

Even though industrial hygienists are not professional videographers, video editing software allows for the production of quality training videos, based on the actual job and exposures (Rosén et al. 2005), which can have a long-lasting effect (Kuhl and Dobernowsky 2011). Multimedia options are available that can address various learning styles. Electronic documents or reports with video illustrations or screenshots can be employed (Rosén et al. 2005; Cecala et al. 2013). In Europe, PIMEX was initially used to develop training films (Rosén 1993) and, later, video-illustrated case studies were distributed via the Internet (Rosén and Andersson 2009; Andersson and Rosén 2014). Libraries of PIMEX films are excellent resources for risk communication in Europe (Winkes 2015). Investigators have used VEM in vocational training schools (Andersson and Rosén 2014) and distance learning (Rosén et al. 2005), and VEM has been recommended for teaching students about safe procedures in academic pharmaceutical research laboratories (McGovern 2004). VEM allows targeted training to multiple audiences including workers, employers, trade organizations, schools, and unions (Rosén et al. 2005).

The output from EVADE can help managers tailor their communication to individual workers and develop mutual strategies to reduce exposure, empowering workers to engage in protecting their health (Haas et al. 2016b). The specificity of the feedback increases worker engagement and workers are often surprised at what actions can produce high levels of exposure (Haas et al. 2016a).

**Techniques and methods for VEM**

**Equipment**

For stationary cameras with either area or personal sampling, positioning is important to optimize the field of view so the worker’s actions can be observed along with external factors influencing aerosol generation and control. Multiple cameras with wide-angle and close-up views can enhance the observations (Walsh et al. 2009). With wearable cameras, where to mount the camera is also important. During NIOSH Helmet-CAM studies, they used a small point of view (POV) video camera with a separable lens that can be attached to the worker’s shoulder or placed on the worker’s helmet using a flashlight connector (Cecala et al. 2013; Reed et al. 2014). NIOSH investigators recommend taping the camera in place to stabilize it and maintain alignment (Cecala et al. 2020). Adequate lighting must be available and some have used infrared lights in low light conditions and set their camera for night shots (Walsh et al. 2009; Reed et al. 2014).

Synchronization between the video camera and aerosol monitor needs to be optimized and adjusted.
to the response time of the monitor (Rosén et al. 2005). Although some VEM systems such as EVADE (Haas et al. 2018) allow post-production offset time adjustments, an important task is to configure and synchronize the DRI with the video equipment. Clocks must be accurate on each device. Synchronization over hours requires aerosol or other monitors to have quick response times (Rosén et al. 2005). Response time is affected by the emission and the sampling device; it is the time it takes for the emission to reach the inlet of the monitor plus the time it takes for the monitor to respond to that input (Gressel et al. 1993; Rosén et al. 2005). Some systems provide synchronization automatically while other systems link the time stamp of the camera with that of the monitor or allow manual synching in the software (Rosén et al. 2005; Haas et al. 2018). Loss of timing problems have occurred with aerosol monitors if their batteries are expended; however, if the instrument and camera are started contemporaneously, the files should be analyzable (Reed et al. 2014). New or fully charged batteries for the monitor and camera are recommended (Reed et al. 2014).

Area sampling around the worker’s breathing zone can be done (Vosburgh et al. 2011) or a personal DRI can be used (Walsh et al. 2000; Echt et al. 2002; Walsh et al. 2009; Garcia et al. 2014; Haas and Cecala 2015; Douwes et al. 2017; Laskaris et al. 2019). As noted in Supplemental Table 1, for VEM studies almost all authors used photometers, and over two-thirds used personal DRIs on the worker. Depending on the VEM system, data from multiple DRIs can be compared (Walsh et al. 2009). Contemporary wearable DRIs have overcome issues such as instrument size, portability, signal output, specificity, and response time cited by earlier researchers (Gressel et al. 1993). Workers can have instruments mounted in harnesses, packs, or on helmets, and researchers have used carts and bicycles to move devices throughout the workplace for area sampling (Rosén et al. 2005; Walsh et al. 2009). The worker’s movements must be considered to ensure that neither the camera nor a DRI interferes with safety or job tasks (Rosén et al. 2005). Systems with telemetry, external data loggers, and video cameras may not be intrinsically safe so may not be used in areas requiring explosion protection (Walsh et al. 2000; Reed et al. 2014).

Wireless transmission of DRI data can be used, but data-logging is often preferred to simplify the amount of material carried by the worker and to avoid radio interference/incompatibility with existing systems or electromagnetic fields within the workplace (Rosén et al. 2005; Walsh et al. 2009; Hedlund et al. 2015). In some environments, such as a cleanroom or a hazardous situation (e.g., asbestos removal), wireless technology can be beneficial (Rosén et al. 2005; Walsh et al. 2009).

**File considerations**

The longer one films, the larger the files that will be produced. Some researchers using EVADE have limited their time to 1–2 hr although the software can deal with larger files created over many hours (Haas and Cecala 2017).

Initial systems generated large files that were difficult to send or store although DVD production and compression technology has addressed this issue (Rosén et al. 2005). A lower setting for video quality can result in smaller file sizes and the type of file affects size (Reed et al. 2014). For the same duration video, avi, and wmv video file formats are generally smaller than high-definition mp4 files (Reed et al. 2014).

The VEM system may limit the type of output files from the camera and DRI. For example, with EVADE, any small video camera can be used that has a file output of avi, wmv, or mp4 with a secure digital (SD) memory card of at least Class 6; Class 10 is advised (Reed et al. 2014). EVADE accepts data files in csv format (Haas et al. 2018) as do other systems (VideoLogix 2021). Most output from DRI can be downloaded and saved as csv files in Excel for data analysis and some editing of the data may be needed before inputting it into VEM software. EVADE requires a comma-delimited file (csv) labeled in order by column: data point number, date, time, and dust concentration (Reed et al. 2014).

**Post-production and statistical considerations**

Post-production editing can be done within some VEM systems while others use video editing software (Rosén et al. 2005). Over time, the software has become more user-friendly. EVADE links the video and respirable dust monitor output and its operation are similar to video editing software such as Camtasia. EVADE is easy to understand and an excellent tutorial is available on the NIOSH website (Haas et al. 2018). The csv file produced from the downloaded aerosol monitoring data and the mp4 or avi file copied from the camera is imported into the working directory of the computer (Reed et al. 2014). After entering the video and data files into EVADE or other VEM systems, industrial hygienists, workers, and managers can immediately evaluate the integrated output and adjust
the actions contributing to dust exposure (Haas and Cecala 2015).

Early on, the issue of autocorrelation with real-time monitoring was noted and investigators incorporated statistical methods to address this issue (Gressel et al. 1987; O’Brien et al. 1989; Heitbrink et al. 1993). Some current statistical analyses addressing autocorrelation can exceed computer processing capacity because of large VEM data sets (Douwes et al. 2017). To deal with this problem some have included one out of 10 or one out of five observations and checked validity by repeating this type of analysis (Douwes et al. 2017).

**Barriers to adoption**

Depending on a company’s IT security infrastructure, it may not allow or permit the usage of particular instrument wireless technologies and software due to potential security vulnerabilities. Some companies will not allow any cameras due to security concerns or collective bargaining agreements. Also, in a study assessing EVADE, some workers felt they were being watched and that the camera and DRI were cumbersome (Haas et al. 2016b). Le Feber et al. (2021) found that of all new workplace technologies, employees viewed video monitoring as the most intrusive. Employers take videos of employees for many reasons and this has resulted in pushback and occasionally legal action (Jenero and Mapes-Riordan 1992). Courts have ruled that when used to develop safer and more efficient work practices, worker privacy is not violated by taking videos (Jenero and Mapes-Riordan 1992). Equipment needs to be comfortable for the worker and be able to withstand the occupational environment (Walsh et al. 2000). VEM is more useful in addressing exposures affected by worker behaviors than those addressed by general ventilation or other plant-wide controls (Rosén et al. 2005). To be a successful endeavor, VEM requires an understanding of human factors and cooperation among workers, managers, and occupational health and safety professionals (Hedlund et al. 2015; Galey et al. 2020).

The expense of a VEM system may be a concern. There is an upfront cost to purchase or rent the DRI but devices/software to integrate the video and csv files cost less than $2,000 or one can use the free NIOSH software (McGlothlin 2009; Haas et al. 2018; VideoLogix 2021). A small- or medium-sized company may not want to purchase a system, however, they could rent it and/or hire a consultant with exposure visualization experience (Kuhl and Dobernowsky 2011; Rosén et al. 2005). Enhancing the design and acceptance of control technologies can offset the expense of the services or purchase (Rosén et al. 2005). Industrial hygienists can advocate for VEM by showing case studies of how it worked (Rosén et al. 2005).

**Summary**

This review is designed to help OEHS professionals expand their application of DRI with an extensive collection of articles, information, and guidance. DRIs can assist occupational health and safety professionals in tackling complex workplace situations. Over the years, the evaluation of controls has been one of the most common and most productive applications of DRIs. DRIs and control technologies have advanced and, as a result, workers are better protected. These control devices and methods can be continually monitored and improved using even more sophisticated DRI technologies as work environments evolve and change in the future.

Industrial hygiene decision-making about workplace aerosols is aided by ACM. As with any other exposure metric, if we underestimate or overestimate aerosol concentrations we may make poor decisions regarding control strategies, wasting money, or more importantly, putting workers at risk (Koehler et al. 2017). Selecting appropriate calibrated DRI, choosing fine grids close to sources, using brief sampling campaigns, replicating measurements, assessing temporal variability, interpolating appropriately by using mapping programs, and conveying the data properly can provide excellent ACM that lead to good decision-making and improved worker protection.

VEM was predicted by now (2022) to be much better incorporated into standard industrial hygiene practice (McGlothlin 2005). However, VEM can be a catalyst for changing the workplace (Rosén et al. 2005). VEM can determine why and how workers are exposed (Gressel et al. 1993). It empowers workers to adapt their work in an iterative method until they reduce their exposure and provides a supportive environment that can promote a health and safety cultural shift (Kuhl and Dobernowsky 2011; Prezant 2011; Haas and Cecala 2015). As McGlothlin (2005, 2009) notes, video exposure monitoring can be used in tandem with integrated sampling and has led to cost-effective sustainable controls, the development of an effective feedback mechanism of continuous workplace improvement, and enhanced communication between industrial hygienists, workers, and management.
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