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Real-time diesel particulate monitor for underground mines

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Abstract

The standard method for determining diesel particulate matter (DPM) exposures in underground metal/ nonmetal mines provides the average exposure concentration for an entire working shift, and several weeks might pass before results are obtained. The main problem with this approach is that it only indicates that an overexposure has occurred rather than providing the ability to prevent an overexposure or detect its cause. Conversely, real-time measurement would provide miners with timely information to allow engineering controls to be deployed immediately and to identify the major factors contributing to any overexposures. Toward this purpose, the National Institute for Occupational Safety and Health (NIOSH) developed a laser extinction method to measure real-time elemental carbon (EC) concentrations (EC is a DPM surrogate). To employ this method, NIOSH developed a person-wearable instrument that was commercialized in 2011. This paper evaluates this commercial instrument, including the calibration curve, limit of detection, accuracy, and potential interferences. The instrument was found to meet the NIOSH accuracy criteria and to be capable of measuring DPM concentrations at levels observed in underground mines. In addition, it was found that a submicron size selector was necessary to avoid interference from mine dust and that cigarette smoke can be an interference when sampling in enclosed cabs.

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Introduction

Exposure to diesel particulate matter (DPM) is a health concern for miners since it is classified as a potential occupational carcinogen by both the National Institute for Occupational Safety and Health (NIOSH) and the Environmental Protection Agency (EPA).[1–4] In addition, diesel exhaust has been potentially linked to other chronic and acute adverse health conditions such as asthma and eye irritation.[5–8] Since underground miners work alongside diesel equipment in a confined environment, they are correspondingly exposed to some of the highest levels of diesel exhaust in the country.[2,9] Therefore, the Mine Safety and Health Administration (MSHA) promulgated a rule to limit exposures of metal/nonmetal underground miners to DPM to an eight-hour time-weighted average (TWA) of 160 μg m^{-3} total carbon (TC).[10,11]

The standard method for determining DPM exposures is to collect the particulate onto a quartz fiber filter for an entire shift and then analyze for elemental carbon (EC) and TC using NIOSH method 5040. TC is used as a surrogate to determine DPM exposures because direct DPM measurement is not sufficiently accurate and because TC represents over 80 percent of DPM.[11–13] However, TC can be influenced by non-DPM organic aerosols such as cigarette smoke and oil mist. Therefore, in some cases, MSHA uses submicron EC as an alternative surrogate because it is selective to DPM in underground mines and is a major component of DPM. Consequently, the final eight-hour TWA permissible exposure limit (PEL) is a TC value that, in order to avoid the influence of interferences, is determined in two ways.[15] In the first test, a full-shift personal sample is collected and sent to a laboratory for analysis of EC and TC using NIOSH method 5040. In the second analysis, the EC concentration of the personal sample is multiplied by a conversion factor to calculate an equivalent TC value. If both the calculated TC value and the measured personal TC are above 160 μg m^{-3}, the mine is out of compliance.

Although NIOSH method 5040 is an accurate method for determining DPM exposures, it only provides the average concentration over an entire working shift, and several weeks might pass before results are obtained. The main problem with this approach is that it only indicates that an overexposure has occurred rather than providing the ability to prevent an overexposure or even detect its source. Conversely, real-time measurement with readout capability would provide workers with almost instantaneous information to identify the major factors contributing to overexposures and to allow timely deployment of engineering controls. As an example, using NIOSH method 5040, it would take weeks to determine the effect of ventilation changes used to reduce DPM. By the time the data are analyzed, the miners could be working in different sections of the mine, and the ventilation could be different due to changes in atmospheric conditions. In contrast, real-time analysis would allow ventilation to be re-directed to provide timely DPM dilution.

One approach that has been taken for real-time DPM analysis is to utilize the Thermo Scientific Personal Dust Monitor (PDM).[16] The PDM is a portable instrument which uses a tapered element oscillating microbalance (TEOM) technology to measure particulate mass. The PDM is utilized to provide continuous mass measurements of respirable dust in coal mines. It has been shown by extensive field measurements to meet the NIOSH accuracy and precision criteria for field instruments for dust measurements.[17,18] In a study performed in coal mines in Australia, an impactor with a 0.8 μm cutpoint at 1.7 lpm was used to separate the DPM from the coal dust and thus enable the PDM to measure ambient DPM mass concentrations. The samples were mostly collected during longwall moves when the dust concentrations were below 500 μg m^{-3}. Under these conditions, the PDM seemed to measure DPM well. At certain concentrations, however, dust may still be an interference. For example, in studies performed at a NIOSH Pittsburgh laboratory, two different coal dusts were evaluated and about two to four percent of the respirable dust penetrated through the impactor.[19] This would result in a bias of 20–40 percent when sampling DPM in dust concentrations at the compliance levels (200 μg m^{-3} DPM and 2000 μg m^{-3} dust). In metal/nonmetal mines, the dust concentrations commonly can be over 2000 μg m^{-3}, resulting in a greater interference to DPM measurements.[19] In addition, in metal/nonmetal mines, cigarette smoke and oil mist can also cause interferences to the PDM measurements.

Light-scattering instruments have also been used for realtime DPM analysis but with highly variable results.[20–27] DPM measurements *via* light scattering can be influenced by humidity, cigarette smoke, oil mist, composition and particle size of aerosol, and dust at certain concentrations, even when an impactor is used.[23–27] Analysts have corrected for the effects of humidity, composition, and particle size of the aerosol when using light scattering for dust measurements by performing a field calibration.[22–24] This usually entails collecting a standard sample (*e.g.*, gravimetric for dust) along with the light-scattering instrument and calibrating the light-scattering data with the standard results. The problem with this correction method is that it extends the analysis time since the real-time data from the light scattering cannot be evaluated until the standard sample measurement is completed. Contrary to humidity and aerosol composition, analysts using light scattering instruments have not developed a method for addressing cigarette smoke, dust, or oil mist in underground mines. However, researchers have reported filter-based methods using multi-wavelength light extinction to determine cigarette smoke and some dusts concentrations in the presence of black carbon in atmospheric samples.[28–30] In order to use these methods to correct for interferences of DPM in occupational settings, further research and optimization would be necessary.[29]

Borak *et al.* evaluated the Aethalometer for determining realtime DPM concentrations at three occupational settings including one underground mine.[31] The Aethalometer is a filter-based method which measures real-time black carbon in the atmosphere *via* absorption. Borak *et al*[31] found a correlation between the Aethalometer and NIOSH method 5040 but not agreement. Therefore, the Aethalometer would need to be calibrated before being used to measure DPM concentrations in occupational settings. The authors also found problems with the pump and that the instrument was affected by vibration. In addition, the power requirements and bulkiness are limitations of this instrument in relation to personal sampling. In the past few years, Magee Scientific introduced a miniature version, the micro-Aethalometer, which can be used for measuring personal exposures to black carbon.[32] However, besides the need for calibration, this instrument lacks the dynamic range to measure DPM concentrations present in underground mines. Other limitations are that it does not have the readout capability or size selection capability necessary to limit the influence of dust present in underground mines.

In order to measure DPM concentrations in underground mines and possibly other occupational settings, the Office of Mine Safety and Health Research (OMSHR) developed a person-wearable real-time EC monitoring instrument. EC was chosen as the analyte since this fraction is a major portion of DPM, is not prone to interferences, and, as previously stated, is one of the surrogates used by MSHA for compliance sampling. Filter-based laser extinction was determined to be a feasible method because EC concentration is proportional to optical density and also because this technique is simple and can be adapted for a small instrument. With a limited and preliminary dataset, the first-generation instrument demonstrated good agreement (within ten percent) with the standard method for measuring EC from DPM (NIOSH method 5040 (ref. 33)).[34,35] This initial success launched the manufacturing of a pre-commercial version, which was produced by FLIR Inc. Laboratory and field testing was subsequently performed on a beta prototype developed by FLIR. Based on the findings of these studies, a commercial version of the monitor was developed, tested, and is now available. This paper provides detailed laboratory analysis of the commercial version (Airtec) including calibration curve, NIOSH accuracy criteria, limit of detection (LOD), dynamic range, and responses to potential interferences. A future paper will discuss the results of field evaluations.

Methods

Description of Airtec

The Airtec measures light extinction, which incorporates the effects of light absorption and scattering. With DPM particles only, the absorption will be the dominant effect on light extinction. Light scattering may have more of an influence if other scattering aerosols are collected with the DPM.[36]

The Airtec device (see Fig. 1) weighs approximately 1.5 lbs and can be worn by a worker or positioned for area sampling. A diaphragm pump draws ambient air at a set flow rate that enables a pre-selector to make around a 1 µm size cut. Conductive tubing allows EC to reach the Teflon membrane filter without sticking to the tubing walls. The Teflon membrane filter is housed in a specially designed cassette that has a defined volume chamber as well as a carefully constructed flow path to achieve uniform distribution of EC on the Teflon filter. Teflon filters were chosen to minimize the influence of absorption and light scattering from the filter material. A laser with a wavelength of 650 nm penetrates through the sample while collecting DPM. Optical density is converted to µg of EC collected on the filter using a calibration curve.

The Airtec displays the five-minute rolling average EC concentrations. Every minute during sampling, the voltage from a point is divided by the initial voltage (set at the beginning of the sampling period) to calculate the transmission. The optical density (−log(transmission)) is then multiplied by the calibration factor to determine the µg EC collected. The EC collected five minutes previously is then subtracted from the µg EC at this time. This number is then inserted in the following equation to determine the five-minute average concentration:

$$\mathrm{EC}\left(\mu\mathrm{gm}^{-3}\right)\ 5\,\mathrm{minute}\ \ \mathrm{average}=\frac{\mathrm{EC}\,(\mu\mathrm{g})}{\mathrm{flow}\ \ \mathrm{rate}\,(\mathrm{lpm})\times 5\,\mathrm{min}}\times 100 \quad (1)$$

A data point is collected every minute, which represents the average concentrations over the previous five minutes. Depending on the limit of quantification (LOQ) needed, a ten-minute and 15 minute rolling average may be desirable because the longer times provide more sensitivity. Eqn (1) is also used when calculating these longer times; instead of five minutes, ten or 15 minutes is used as the sampling time, and the EC from ten or 15 minutes earlier is subtracted from the current EC collected to determine the µg of EC.

The Airtec also records and displays the eight-hour TWA EC concentration, which is calculated by inserting the µg of EC collected into the following equation:

$$\mathrm{EC}\left(\mu\mathrm{gm}^{-3}\right)\ 8\,\mathrm{h}\ \mathrm{TWA}=\frac{\mathrm{EC}\,(\mu\mathrm{g})}{\mathrm{flow}\ \ \mathrm{rate}\,(\mathrm{lpm})\times 480\,\mathrm{min}}\times 100 \quad (2)$$

The Airtec has the capability to sample at 1.7 lpm (high flow) and 0.85 lpm (low flow) in order to expand the dynamic range. The 1.7 lpm flow rate allows for a more sensitive measurement, and the 0.85 lpm allows a larger 8 h TWA concentration to be measured. The 1.7 lpm flow rate results in a 0.8 µm cutpoint with the impactor currently used, and the 0.85 lpm flow rate results in about a 1 µm cutpoint.

Calibration curve

A calibration curve was developed for the Airtec (commercial version), which was accomplished by collecting DPM onto quartz fiber filter samples used for determining EC concentrations *via* NIOSH method 5040 and Airtecs simultaneously in a Marple chamber, as described in a previous publication.[37]

At least three Airtecs were set up and checked for flow rate. Tubing was attached to the instruments and inserted into the chamber. In addition, three-piece cassettes (Sureseal plastic cassettes containing quartz fiber filters with cellulose backing pads) to measure EC *via* NIOSH method 5040 were placed inside the chamber and attached to tubing, critical orifices (flow rate set at 1.7 lpm), and a vacuum pump. The instruments and vacuum pump were turned on. A 4-cylinder Kubota engine with a Genset applying a load at 50 percent was then operated for 15 minutes, after which part of the diesel exhaust was inserted into the chamber to be collected by the Airtecs and NIOSH method 5040 samples. When the Airtecs showed a reading of about an eight-hour TWA concentration of 10 µg m^{-3}, two of the NIOSH method 5040 samplers were turned off. This was repeated for eight-hour TWA concentrations around 20, 50, 100, 200, 300, and 400 µg m^{-3} EC. The quartz fiber filter samples were analyzed for EC *via* NIOSH method 5040 at NIOSH OMSHR Pittsburgh. The procedure was repeated seven times for EC concentrations ranging from about 20–400 µg m^{-3}.

The data from each Airtec was downloaded to a laptop. The voltage reading from the Airtec when each NIOSH method 5040 sample was stopped was divided by the initial voltage to determine the transmission of the filter during the time the NIOSH method 5040 sample was collected. The optical density was determined by taking the −log of the transmission. The NIOSH method 5040 EC results as well as the Airtec results were averaged, and both were plotted to develop a calibration curve.

NIOSH accuracy criteria

Kennedy *et al.* developed a document containing the NIOSH accuracy criteria, which requires an average bias within ten percent and an accuracy within 25 percent with 95 percent confidence when comparing a new analytical method to a standard method.[38] The document also provides recommended procedures for determining the bias and accuracy. Therefore, the next part of the Airtec evaluation was to determine if the instruments would meet this criteria when compared to NIOSH method 5040.

At least eight Airtecs were attached to conductive tubing that was inserted into the Marple chamber. In conjunction, the same number of cassettes (Sureseal three-piece cassette) containing quartz fiber filters was placed in the chamber to collect EC samples for NIOSH method 5040 analysis. These cassettes were attached to critical orifices and a vacuum pump *via* tubing to collect a sample at 1.7 lpm. The Airtecs and the quartz fiber filters were turned on and run at 1.7 lpm. Diesel from a Kubota engine (50 percent load) was inserted into the chamber after warming the engine for ten minutes. When the Airtecs indicated that a 10 μg m^{-3} eight-hour TWA was collected, both the Airtecs and NIOSH method 5040 samples were turned off. This was repeated for EC concentrations of about 100, 120, and 240 μg m^{-3}. These concentrations were recommended in the NIOSH publication for determining accuracy. The bias, precision, and total accuracy were determined using the equations and nomogram in the NIOSH publication.[38]

LOD/LOQ

The LOD and LOQ were determined by running eight Airtecs for eight hours in the laboratory where no EC was present. The eight-hour TWA of each Airtec was calculated after which the standard deviation was determined and multiplied by three to establish the LOD and by ten to determine the LOQ. The five-minute, ten-minute, and 15 minute rolling averages were calculated for the entire eight hours. The standard deviation was then determined for each concentration and multiplied by three for LOD and ten for LOQ.

Interferences

Absorbing particles, non-absorbing particles, and humidity have been shown to interfere with filter-based absorption techniques.[36,39–42] Non-absorbing particles can affect the light extinction by light scattering or can enhance the absorption by multiple scattering which causes more opportunity for light absorption.[36] The influence of these effects depends upon filter type, light wavelength, and aerosol.[36,39–42] Therefore, the influence of these potential interferences specifically for the Airtec needs to be evaluated.

Aerosols present in underground mines which could be interferences would be dust, humidity, cigarette smoke, and oil mist.[14,20] In this paper, the effects of these parameters on the Airtec were evaluated by introducing these interferences into a Marple Chamber and recording the response of the Airtecs to these aerosols. In addition, DPM was inserted with these interferences, and the Airtecs were compared to NIOSH method 5040 samples in this type of atmosphere.

Dust

In order to evaluate the effects of some dusts on the Airtec, a dust collected from a gold mine was sent to Penn State University to be sized to a particle size distribution representing what was observed at the gold mine. The particles were then inserted into a TSI 3400 Aerosol generator. A previous publication provides more details, such as particle size distribution, on the dust used.[34] A Thermo Scientific Tapered Element Oscillating Microbalance (TEOM) 1400 was set up to collect the total dust mass concentration inside the chamber. Three SKC Inc. DPM cassettes containing quartz fiber filters were placed inside the chamber and connected to critical orifices for 1.7 lpm flow rates to collect NIOSH method 5040 EC samples. SKC DPM cassettes were chosen because they segregate the dust and diesel to obtain an accurate DPM measurement *via* NIOSH method 5040 in the presence of mine dust.[37]

Conductive tubing was extended from nine Airtecs into the chamber. In order to evaluate the response of the Airtec to respirable dust, three Airtecs were attached to a Dorr-Oliver cyclone and run at 1.7 lpm. Six Airtecs were attached to an impactor (SKC DPM cassette without the quartz filters and backing pad) to indicate if these size selectors could prevent the interference of dust on the monitors, because these impactors are used to eliminate dust interference on NIOSH method 5040 samples.[11,14,37] Three Airtecs with impactors were operated at 1.7 lpm and three at 0.85 lpm in order to determine the effects of dust at the two operating flow rates. The flow rates for each sample were checked and recorded.

The TEOM and Airtecs were turned on but the NIOSH method 5040 samples remained off. Dust was inserted into the chamber to the highest level achievable. After about two hours, in addition to the dust, DPM *via* the Kubota Genset at 50 percent load was inserted into the chamber, and the NIOSH method 5040 samples were turned on. DPM was collected until the EC would represent a sample at about 100 μg m^{-3} eight-hour TWA. The dust and diesel samplers were then shut down and the chamber was cleared. The SKC DPM cassettes with quartz filters were analyzed for EC and TC *via* NIOSH method 5040 at NIOSH OMSHR Pittsburgh. The data from the TEOM and Airtecs were downloaded. The experiment was repeated using limestone dust, which also was sent to Penn State University to be sized according to what was observed in the field.

Humidity

Another possible interference to real-time measurements is humidity. In order to test the effect of humidity on the Airtec, the humidity in the Marple chamber was increased using a Miller-Nelson Research Control System model HCS-401. Because this alone could not bring the humidity up to the desired 90 percent, water vapor was also inserted into the chamber using a Vicks Humidifier until the humidity was about 90 percent, determined using a Vasaila GM70 gas monitor. DPM was then inserted into the chamber with the Kubota engine at 50 percent load, and NIOSH method 5040 samples (at least 9) using a three-piece cassette with a quartz filter and cellulose backing pad were collected while the Airtecs (at least 7) were operating. The NIOSH method 5040 samples and Airtecs were turned off when enough DPM was collected to represent about 12 μg m^{-3} EC 8 hour TWA. This process was repeated to collect enough EC mass representing concentrations of 120 μg m^{-3} EC and then 240 μg m^{-3} EC. The results from the Airtec and NIOSH method 5040 samples were then compared.

Cigarette smoke

The response to cigarette smoke was determined by first introducing DPM (Kubota Genset at 50 percent load) into the chamber while six Airtecs with impactors and twelve NIOSH method 5040 samplers (SKC DPM cassettes) were running at 1.7 lpm. In addition, a TEOM 1400 was used to measure the total particulate mass concentration. An Airtec and two SKC DPM cassettes stopped sampling after collecting DPM that represented 25 μg m^{-3} eight-hour TWA EC. This process was repeated until an Airtec collected enough EC representing 50, 70, 100, 140, and 200 μg m^{-3} eight-hour TWA. The DPM was subsequently flushed out of the chamber.

Two Airtecs with clean filters and impactors were turned on, and tubing was extended from the instruments into the chamber. Again, the six Airtecs containing different DPM concentrations started sampling inside the chamber as well as six new SKC DPM cassettes for TC analysis of the cigarette smoke. Cigarette smoke was puffed into a metal container (Fig. 2) and then drawn into the Marple chamber. The cigarette smoke was sampled until about 250 μg m^{-3} eight-hour TWA cigarette smoke mass was collected. NIOSH method 5040 samples were stopped periodically throughout the test. At the end of the test, the Airtecs were turned off and the cigarette smoke was flushed out of the chamber.

The quartz filters were analyzed for EC and TC *via* NIOSH method 5040 at NIOSH OMSHR Pittsburgh, and the Airtec and TEOM data were downloaded.

Oil mist

Three Airtecs with no size selector, three Airtecs with submicron impactors, and the TEOM (mass) were turned on and collected the air in the Marple chamber. An oil mist was introduced into the chamber using a TSI 3076 Constant Output Atomizer containing Chevron Aries ISO220, a type of oil used in drills in some metal mines. After about six hours, the samplers were turned off.

In order to determine the influence of DPM combined with the oil mist, enough EC to represent about 100 μg m^{-3} eight-hour TWA was collected with three Airtecs with impactors, three with no size selector, and three SKC DPM cassettes using the same chamber and diesel source described in the Cigarette smoke section, including using the TEOM for determining total particulate mass concentrations. The pumps for the SKC DPM cassettes were stopped. The DPM was flushed out of the chamber, and oil mist was inserted into the chamber (as described above). After about three hours the samplers were turned off.

There is little information on what concentration of oil mist in the chamber would relate to real-world applications. Therefore, a sample was collected in an area of a metal mine where drilling was prevalent but where no diesel vehicles were operating. An SKC DPM cassette attached to an MSA elf pump was worn by a miner who performs pneumatic drilling at a metal mine. On the day of sampling, the miner worked in an area where he was drilling but where no diesel vehicles were operating. The sample was analyzed for EC and TC using NIOSH method 5040 at NIOSH OMSHR Pittsburgh.

Results and discussion

Calibration curve

Fig. 3 presents the calibration data plotting the Airtec results *vs.* EC mass per filter determined using NIOSH method 5040. This graph shows a strong correlation between these two data sets with an R^2 of 0.98. The equation for this line can be used to calculate EC mass from the Airtec measurements. The calculated EC mass can then be inserted into eqn (1) and (2) to calculate the EC concentration in the area being measured. Note that this calibration curve is only pertinent for samples collected with 37 mm Pall Teflon filters, and a revised curve would be necessary if different filter types or sizes are used. The slope and intercept could also possibly be slightly different between instruments.

As also seen in Fig. 3, the correlation between optical density and EC seems to start to diverge from the line when the EC collected onto the filter exceeds 276 µg. At this mass quantity, the aerosol deposit reaches optical saturation to the point that the optical density measurement is inaccurate. Converting 276 µg into concentration, this calibration curve becomes questionable when determining 8 hour TWA EC concentrations over 338 µg m^{-3} at a flow rate of 1.7 lpm or over 676 µg m^{-3} at a flow rate of 0.85 lpm.

NIOSH accuracy criteria

The method used to determine if an instrument meets the NIOSH accuracy criteria was outlined in the Methods section. Although this study was limited by the number of Airtec instruments available, using this data in the equations and nomogram developed by Kennedy *et al.*,[38] the method met the NIOSH accuracy criteria (accuracy of approximately 12 percent at 95 percent confidence). Table 1 presents the biases and coefficient of variations (CV) calculated for the Airtecs using the Kennedy method.

LOD/LOQ

Table 2 presents the LOD for the eight-hour TWA and the 5, 10, and 15 minute real-time measurements. Using the LOQ for the minimum quantifiable concentration and the calibration curve to determine the highest measurable concentration, the dynamic range for the Airtec is 4.75 to 338 µgm^{-3} eight-hour TWA EC at 1.7 lpm and 9.5 to 676 µg m^{-3} eight-hour TWA EC at 0.85 lpm. Though the real-time data has no upper limit, the Airtec can only accurately detect EC concentrations until 276 µg of EC is collected on the filter. This dynamic range is good for most concentrations observed in underground mines.[2,20] However, this instrument could be optimized for other environments; *e.g.*, multiple flow rates and different Teflon filter sizes would enable users to balance sensitivity with filter longevity in order to use the instrument in different types of scenarios.

Interferences

Dust—As seen in Fig. 4, at concentrations greater than 10 mg m^{-3} (MSHA's nuisance dust standard for non-coal mines) metal mine dust resulted in Airtec readings around 100 μg m^{-3} in the absence of DPM and if no size selector was used. However, if a submicron impactor was employed, these dust concentrations did not result in a false positive measurement using the Airtec. When DPM and dust were both present in the test chamber and no size selector was used, the dust resulted in a bias of −109% (see Table 3); however, this bias was reduced to less than ten percent when an impactor was utilized. This approximate 275 μg m^{-3} interference is due to several effects. About 100 μg m^{-3} is probably due to light extinction from the dust particles, as shown by the dust absorbing some of the light when only dust was being collected. The other 175 μg m^{-3} is probably due to several other factors as described below.

DPM can coagulate with dust particles resulting in some of the DPM being collected by the impactor.[43,44] This would result in more DPM being present on the filter with no size selector compared to when an impactor is used. The light extinction would then be greater when no impactor is utilized. The quantitative effect of this phenomenon is not well known but is part of a study being performed currently at NIOSH. Besides coagulation, light scattering could also have contributed to the bias. Bond *et al.* reported that even non-absorbing particles can increase light extinction when deposited on the filter *via* light scattering.[36] This effect resulted in a 2–9% increase in optical density at atmospheric concentrations. Bond *et al.* also reported that scattering of non-absorbing aerosols mixed with the absorbing aerosols can increase light extinction by 20–30%.[36] The authors attributed this to multi-scattering by the particles allowing more opportunities for light absorption. Given the high concentration of dust utilized for evaluating the Airtec, these effects could easily be greater than those reported by Bond *et al.*

Using limestone dust, at the concentrations shown in Fig. 5, the Airtec did not detect the dust whether an impactor was used or not. This dust was not expected to absorb the light but some effect on the light extinction might have been observed due to scattering. This effect was not observed when using the Teflon filter. However, when the mixture of limestone dust and diesel was present in the test chamber, as seen in Fig. 5, the measurement of the Airtec with no pre-selector resulted in higher concentrations of DPM than the Airtec with an impactor. The results from this test (Table 3) convey a −30 percent bias when no pre-selector was employed but less than 10 percent bias when an impactor was used.

One possibility for this bias is that the DPM coagulated onto the dust particles, causing less DPM to be collected by the impactor. Again, this could also be the result of light scattering or enhanced absorption when the dust is mixed with the DPM particles, especially since studies have reported a 30% increase in light extinction due to non-absorbing aerosols even when not embedded in the filter.[36]

Some mine dusts can absorb at 650 nm causing a bias in the Airtec readings. Non-absorbing mine dusts can also cause a bias when comparing Airtec without a pre-selector to the standard method for measuring DPM in mines, which entails using a submicron impactor. This bias could be caused by coagulation, light scattering, or enhanced absorption due to multi-scattering. The submicron impactor eliminated any interference issues with mine dust. Therefore, when using the Airtec in underground metal/nonmetal mines, an impactor (or equivalent size selector) should be used to avoid possible interference from dust.

Humidity—Table 4 presents the bias results comparing the Airtec with NIOSH method 5040 in an environment of DPM and 90 percent humidity, potentially present in some mines during the summer months. The bias was less than 10 percent (within bias range normally observed (see NIOSH accuracy criteria section)) for two of the concentrations but was 15.8 percent for the lowest concentration. However, the confidence intervals for the two lowest measurements overlap, indicating no statistical difference in the two values. Therefore, it was determined that the Airtecs were not affected by high humidity.

Cigarette smoke—As seen in Fig. 6, when only cigarette smoke was present in the chamber at concentrations well above what is observed in underground metal/nonmetal mines, it was not detected by the Airtec. There is limited data on cigarette smoke concentrations in underground mines, but one study showed that the eight-hour TWA TC concentrations were typically 50–100 μg m^{-3} and at times 250 μg m^{-3} higher in enclosed cabs with smokers compared to enclosed cabs with non-smokers.[14] Another study, in an experimental mine, quantified that each cigarette may contribute up to 5 μg m^{-3} eight-hour TWA TC when smoking occurs in an area with dimensions of approximately 18.5 feet wide and 6.2 feet high (115 ft^2 cross-sectional area) and when the ventilation was 6000 cfm.[46] To put this into perspective, if 14.1 cigarettes (average number of cigarettes per day per smoker in California in 2004)[47] is used to represent the number of cigarettes smoked in a shift, the cigarette smoke concentration within a few feet of the miner would be about 70 μg m^{-3} eight-hour TWA TC for a ventilation rate of 6000 cfm and a 115 ft^2 cross-sectional area. Since most mines have a larger cross-sectional area and higher ventilation rates,[46,48–50] the concentration of cigarette smoke would be expected to be lower.[46]

Cigarette smoke on the Teflon filter did not affect the light extinction in the Airtec. However, when mixed with DPM particles, cigarette smoke was a potential interference. As seen in Fig. 6, when DPM is on the filter, the Airtec does detect some of the cigarette smoke. As mentioned earlier, studies have shown that non-absorbing particles can affect light extinction due to light scattering and multi-scattering of the particles, increasing the opportunity for light absorption.[36,41,42] Therefore, one plausible explanation for the interference of cigarette smoke is that the multi-scattering of the cigarette smoke particles could increase the amount of light exposed to the DPM particles, resulting in more light absorption.

As seen in Fig. 7, adding cigarette smoke to the environment after collecting DPM on the Airtec filter resulted in two trends. One trend was identified when enough DPM mass representing concentrations between 25 and 50 μg m^{-3} eight-hour TWA EC was present on the filter and another when DPM mass representing greater than 70 μg m^{-3} eight-hour TWA

EC was collected. The graphs show that when sampling at concentrations of DPM around the final permissible exposure limit (120 μg m^{-3} EC), concentrations of cigarette smoke between 50 and 250 μg m^{-3} TC (observed when smoking in enclosed cabs) can result in readings between 8 and 98 μg m^{-3} of interference on the Airtec, which would result in a bias between 7 and 81 percent. When exposed to concentrations of cigarette smoke below 50 μg m^{-3} TC, the bias would then be below 7 percent when sampling at the DPM PEL.

At this time, in underground mines, the concentrations of cigarette smoke (above 50 μg m^{-3} TC) where the resulting bias is of concern have only been observed when sampling smokers in enclosed cabs. One way of avoiding the problem would be to simply have the miners not smoke in the enclosed cab during sampling. A topic of a future study would be to determine the actual effects of the cigarette smoke on the instrument in the field. Then, some correction methods may be investigated. For example, other studies have had success with using multi-wavelengths to determine the contribution of cigarette smoke in the presence of black carbon.[28–30]

Oil mist—As can be seen in Fig. 8a and b, the Airtec did not detect oil mist even if DPM was present on the filter. For these tests, the concentration of oil mist in the chamber was the highest achievable concentration with the experimental setup and was close to what was observed in a metal mine. In an area in a metal mine where oil mist was present but where there was little DPM, 164 μg m^{-3} OC was measured. DPM contributed little to this OC value as seen by the EC value only being 16 μg m^{-3}, which converts to about 21 μg m^{-3} TC or 5 μg m^{-3} OC of the sample from DPM using the TC/EC ratio of 1.3 (typical ratio found in mines[14]). The largest submicron OC-containing aerosol in the area was oil mist.

Conclusions

NIOSH has developed a method for measuring real-time DPM concentrations in underground mines by calculating EC concentrations from a laser extinction measurement. The Airtec is a small, lightweight, person-wearable instrument which incorporates this laser extinction method. This instrument has been shown in the laboratory to meet the NIOSH accuracy criteria. In addition, this instrument is not prone to interferences from humidity and oil mist. Laboratory studies have shown that dust can interfere with the instrument measurements if a submicron pre-selector is not used; therefore, a submicron impactor or some comparable pre-selector should be used with the instrument when measuring DPM in underground mines. Cigarette smoke was also shown to cause a measurement bias greater than ten percent under specific circumstances with this instrument. However, the concentration of cigarette smoke where this is a concern has only been observed when collecting samples inside enclosed cabs where miners are smoking. This bias can be avoided by preventing miners from smoking inside the enclosed cab during sampling. Other precautions and potential correction methods to be used with this instrument are currently being investigated. The next step in evaluating the Airtec is to test its reliability during field operation in underground mines. This type of study may also provide a better idea of the role of potential interferences such as cigarette smoke on the data and will be a topic of a future study.

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Fig 1.
Picture of the Airtec, the commercial version of the real-time EC monitor.

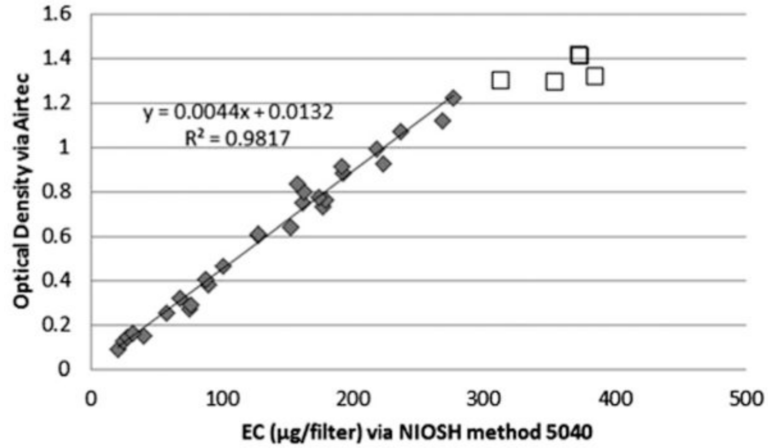


Fig 2.
Apparatus used to introduce cigarette smoke into chamber.

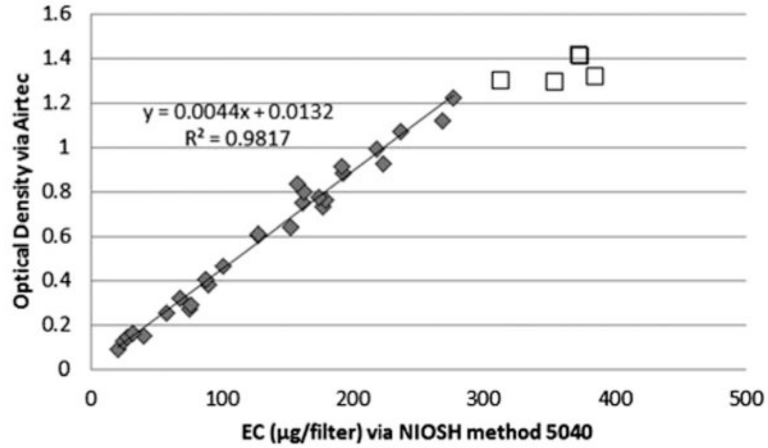


Fig 3.
Optical density *vs*. EC in (µg per filter) including points when the µg of EC on the filter exceeds 276 µg.

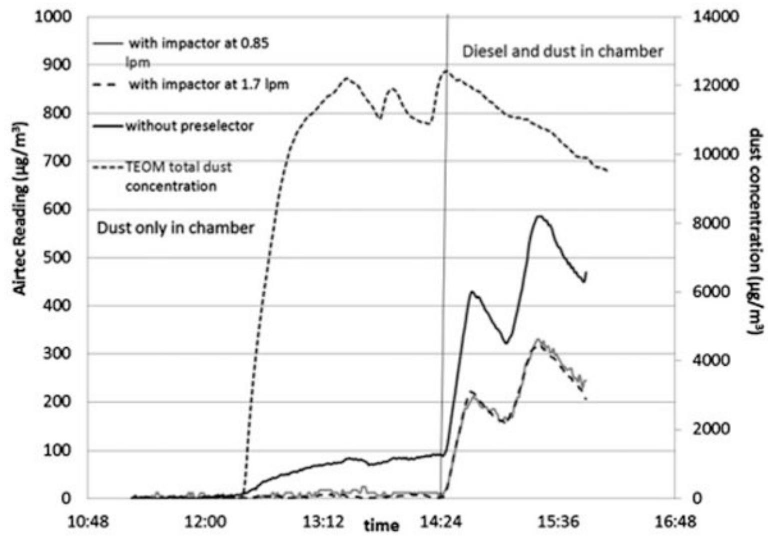


Fig 4.

The concentration of total dust from a metal mine in the test chamber, with and without DPM, and the measurement of the Airtecs at the same time.

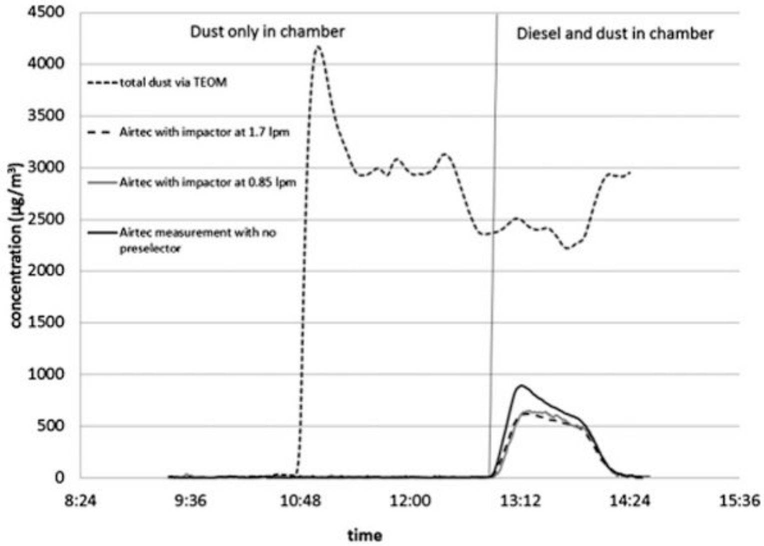


Fig 5.

The concentration of limestone dust and DPM in the test chamber along with the Airtec measurements.

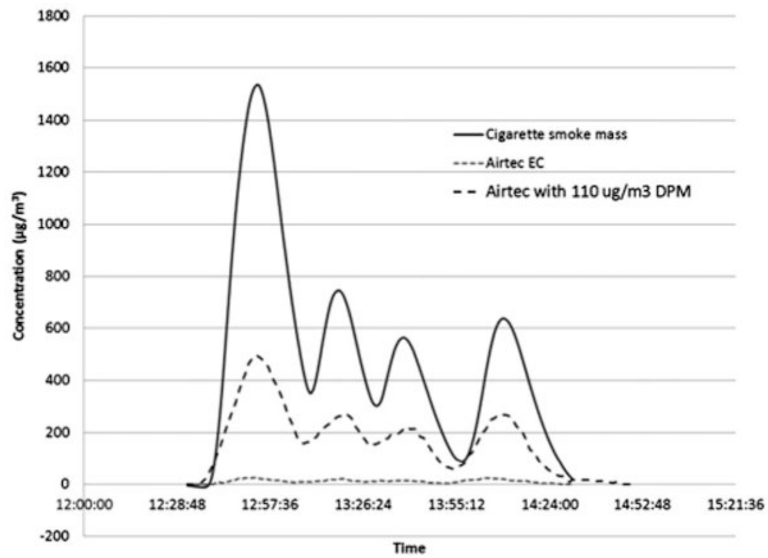


Fig 6.

The response of the Airtec to cigarette smoke.

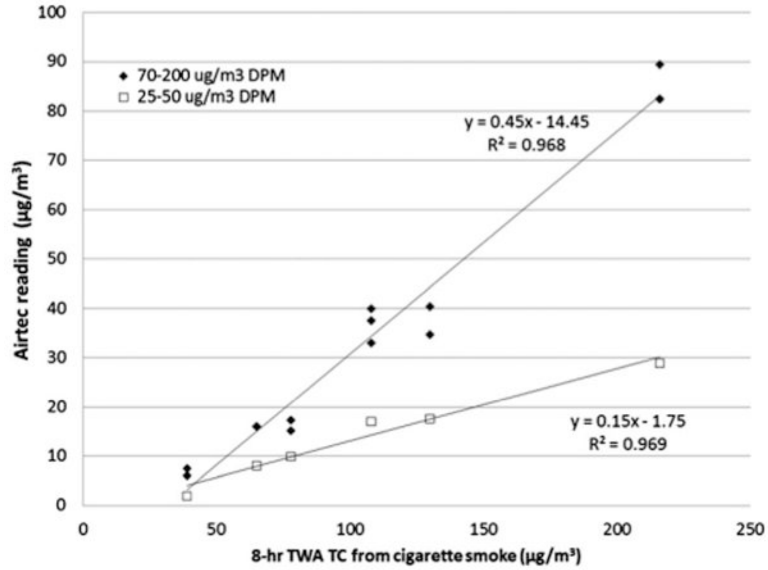
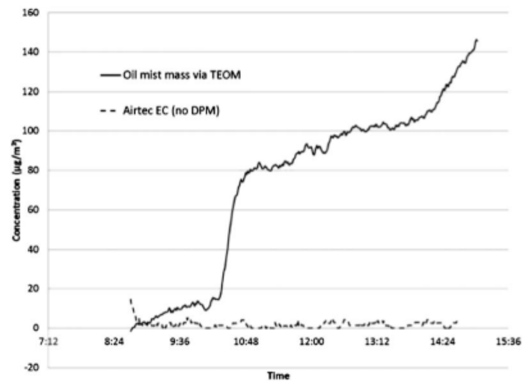
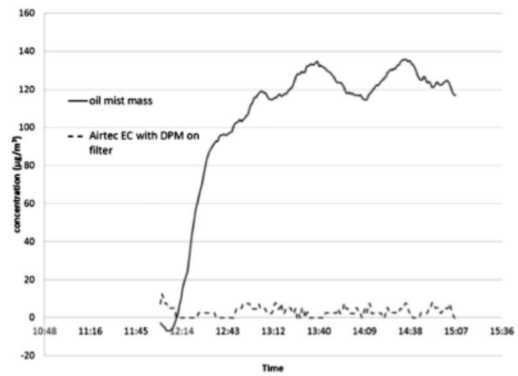


Fig 7.

The concentration measured by the Airtec when sampling in just cigarette smoke after the collection of EC from DPM.



(a)



(b)

Fig 8.

Airtec measurement in the presence of oil mist in the test chamber with (b) and without (a) DPM collected on the filter.

Table 1

The bias and coefficient of variation for the Airtecs *vs.* NIOSH method 5040

	NIOSH 5040	Airtec		NIOSH 5040	Airtec
Number of samples	**Average 8 hour TWA EC concentration (μg m^{-3})**	**Average 8 hour TWA EC concentration (μg m^{-3})**	**Bias (%)**	**CV (%)**	**CV (%)**
10	113	107	5.31	2.5	7.8
9	311	282	9.32	1.8	3.7
9	12	13	−8.33	6.1	6.1
8	130	132	−1.54	7.8	4

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Table 2

Airtec limit of detection and quantification

	8 h TWA	5 minute average concentration	10 minute average concentration	15 minute average concentration
LOD (μg m^{-3})	1.42	21.63	13.1	10.04
LOQ (μg m^{-3})	4.75	72.11	43.67	33.47

Table 3

Comparison of EC readings from NIOSH method 5040 and Airtec in the presence of dust and DPM

Dust	Size selector on Airtec	Flow rate	NIOSH 5040 EC ($\mu g\ m^{-3}$)	Airtec EC ($\mu g\ m^{-3}$)	Bias%
Metal	None	1.7	251.20	525.76	−109
Metal	Impactor	0.85	251.20	230.03	8
Metal	Impactor	1.7	251.20	229.87	8
Limestone	None	1.7	621.52	808.72	−30
Limestone	Impactor	0.85	621.52	591.64	5
Limestone	Impactor	1.7	621.52	603.81	3

Table 4

Comparison of Airtec and NIOSH method 5040 results measuring EC in 90% humidity[a]

Average 8 h TWA EC concentration ($\mu g\ m^{-3}$) *via* NIOSH method 5040	Average 8 h TWA EC concentration ($\mu g\ m^{-3}$) *via* Airtec	Bias%
14.39 ± 1.37	16.66 ± 0.91	−15.77
135.87 ± 2.54	122.97 ± 7.73	9.49
229.89 ± 7.32	208.02 ± 8.61	9.51

[a]95% confidence limits: student t × standard deviation/(number of samples)$^{0.5}$.[45]