Visualization of Dust Generation in Outdoor Workplaces Using A Wearable Particle Monitor and Global Navigation Satellite System

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Abstract: We manufactured a wearable particle monitor (WPM), which is a simple and low-cost dust monitor. We aimed to evaluate the usefulness of the device by using it and location information of a Global Navigation Satellite System (GNSS) to measure dust generation in outdoor workplaces. We used nine WPMs and a particle counter KC-52 to measure in parallel the dust concentration diffusing standard particles in a dust exposure apparatus to evaluate the measurability of the WPM, and visualized dust generation in outdoor workplaces to evaluate its usability. We obtained location information using a GNSS in parallel with measuring with the WPM. The measured values of the WPM followed the measured values of the KC-52, with a strong correlation of the values between the KC-52 and each WPM. The discrepancy among devices tended to increase, however, because the measured values of the WPMs increased. For outdoor measurements, we could create a heat map of the relative values of dust generation by combining two data of the WPM and the GNSS. The methods of using the WPM could overview the conditions needed to produce dust emissions in dust-generating workplaces.

Keywords: dusty workplace, heat map, outdoor work environment, particle matter sensor, wearable particle monitor.

Introduction

The number of workers with pneumoconiosis, a typical occupational disease, peaked in Japan in the 1980s and has been decreasing yearly since then [1]. Even in recent years, however, the number of workers with pneumoconiosis newly certified for occupational accident compensation numbered approximately 300 [2], is still relatively high, and 164 workers needed to retire permanently owing to pneumoconiosis in 2019 [3]. Various mitigating measures have been implemented in many dust-generating or dust-handling workplaces to prevent adverse health effects caused by dust exposure, including medical examinations to

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detect and prevent pneumoconiosis; measures to prevent dust emission in the workplace; the measurement of dust generation to which workers are exposed; occupational health education; and occupational health management. Occupational health and safety laws and regulations in Japan stipulate that periodic measurements should be performed in working environments where workers handle or are exposed to harmful substances, including respirable dust, after which appropriate improvement measures need to be taken based on the results of the evaluation. These measures have led to significant improvements in working environments [1, 4, 5], but the measurements of various harmful substances in the working environment are usually conducted at several fixed points over a short, fixed period of time; therefore, several workplaces have not been subjected to such measurements. In dust-generating or dust-handling work, working environment measurements are applicable to “indoor workplaces where specific dusty work is always performed.” They do not apply to outdoor workplaces, or workplaces where workers handle dust temporarily or for short periods, or workplaces where the source of dust emission moves. As it is well known that adverse health effects from dust exposure occur even in such workplaces [6], it is vital to understand the actual conditions of the work environment and to take appropriate measures to prevent harmful dust exposure.

There has been considerable discussion recently on the implementation of personal exposure measurements in Japan. Personal exposure measurements, such as using personal dust samplers, have already been adopted widely overseas [7, 8]. In Japan, personal exposure measurements have been recommended as a risk analysis method for those handling chemical substances, based on previous findings from overseas [9]. The Working Environment Measurement Law—which regulates the methods for taking measurements in working environments—was partially revised in 2020, with the revisions prescribing selective measurements taken by personal samplers, for several harmful substances [10]. Promoting personal exposure measurements is expected to contribute to the prevention of health problems in workers exposed to harmful substances and should lead to improvements in work practices and environments.

The actual implementation of personal exposure measurement requires instruction from and cooperation with working environment measurement experts, who should have specialized knowledge and skills in the handling of personal samplers. Currently, however, not enough such experts are available in Japan [10]. The NWPS-254 sampler (Shibata Scientific Technology Ltd., Tokyo) is used widely in Japan as a personal respirable dust sampler [11], but the price of the NWPS-254 sampler and its consumables is high, at approximately 196,000 yen [12]. Such technical or economic constraints obviously hinder the widespread application of personal exposure measurements.

Optical particle matter (PM) monitors equipped with low-cost PM sensors are currently available in the consumer market, and several studies have shown that these monitors can predict dust generation [13, 14] and are useful for measuring relative values of dust generation in general outdoor and indoor environments [15–18]. We hypothesized that one novel use for such low-cost PM monitors could be to monitor personal dust exposure for workers in dust-generating workplaces.

In view of the above, we manufactured a wearable particle monitor (WPM) and its applications, a simple and low-cost device, to monitor dust emissions in the work environment in real time and to overview the degree of dust to which workers are exposed. We believe that this device could be useful in promoting effective measures to prevent health problems in workers engaged in dusty work. The aim of our current study was to evaluate the usefulness of this device by conducting measurements in actual outdoor dust-generating workplaces.

**Methods**

**Wearable particle monitor (WPM)**

We produced a WPM (prototype), which is an improved and modified version of the “Pocket PM2.5 Sensor” already marketed by Yaguchi Electric Co., Ltd., converting it into a wearable workplace dust measurement device for this study. The new specifications include: 1. the improvement of both the applications and hardware to enable continuous measurement for more than 3.0 h; 2. the establishment of a data link between the sensor and smartphone via wireless Blue-
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tooth, assuming that dusty workers place the WPM on their chest or shoulder while measuring; 3. the addition of a data storage function inside the hardware for stand-alone use; and 4. the activation of the vibration alarm when the threshold value (manually configurable) is exceeded.

We used a prototype WPM in the experiments in this study. Some specifications of the WPM are as follows: the size of the WPM is $42.5\, \text{mm} \times 32\, \text{mm} \times 24.5\, \text{mm}$, with a weight of approximately 70 g. PM sensors generally use light-emitting diodes (LEDs) as a near infrared (NIR) optical source and calculate the particle mass concentration by detecting the scattering intensity of aerosol particles in a certain space [19]. The PM sensor (SDS 021, Nova Fitness Co., Ltd., Shandong) of our WPM is of the same type, whereas the other specifications include a measurement interval of 1 s, measurement sensitivity of $1\, \mu\text{g/m}^3$, measurement range of $0$–$999\, \mu\text{g/m}^3$, and maximum relative error of $\pm 15\%$ and $\pm 10\, \mu\text{g/m}^3$. A certain mass-concentration conversion factor (K factor) is set by default in the PM sensor of the WPM, and the mass concentration ($\mu\text{g/m}^3$) is displayed and recorded as the measured value. The default value of the K-factor was not indicated in the manufacturer’s specification sheet of the SDS 021, nor was the flow rate indicated. We requested this information from Yaguchi Electric Co., Ltd. as the importing company, but they did not disclose the information. The WPM cannot measure the absolute amount of dust concentration but can determine whether a particular location in the working environment has relatively higher values of dust than other locations. Therefore, the measured value displayed in the WPM was defined as an unitless relative value of dust generation (0–999).

The WPM can check the measured values in real time by launching and connecting to a dedicated smartphone application through Bluetooth low energy (BLE), and a light emitting diode (LED) lamp mounted in the WPM changes color according to the measured value, i.e., the approximate measured value can be checked at any time. The main body of the WPM and the dedicated smartphone application are shown in Figure 1.

**Wearable attachment for WPM**

As the WPM cannot be worn on the human body by itself, a wearable attachment has been fashioned. This attachment was modeled by 3D CAD (Fusion360, Autodesk, Inc., California) and constructed using a 3D printer (Creator3, Zhejiang Flashforge3D Technology Co., Ltd., Zhejiang). When conducting personal dust exposure measurements, sample collection devices must be worn in the respiratory zone, which is defined as “a hemispherical area (usually with a radius of 30 cm) extending in front of the person’s face and centered on a point in the middle of a straight line connecting the two ears” [20]. The device is worn on the upper arm using the wearable attachment for WPM, which is outside of the “breathing zone.” We decided to go ahead with fixing the device on the upper arm for ease of attachment and removal, workability, and convenience. Figure 2 shows a drawing of the wearable attachment.

![Figure 1. Images of the main body of the wearable particle monitor (WPM) and the dedicated smartphone application.](image-url)
for WPM and an image of it being worn. We conducted an experiment at the factory building (temperature: \(\sim 20^\circ C\), relative humidity: 45%, no wind) in the University of Occupational and Environmental Health, Japan to evaluate the effect of both the wearable attachment for the WPM and the area where the WPM is worn. In the experiment, we measured six WPM wearing states, combining two patterns of WPM with and without wearable attachments and three areas (100 cm above the floor area, face side area, and upper arm area). To minimize the change in indoor dust conditions, the measurement for one condition was performed for 1 min and all measurements were performed within 10 min.

**Measurability assessment of WPM**

We thought it would be necessary to verify the measurability of the WPM before conducting dust generation measurements in the work environment. The verification was conducted in October 2019 at the Department of Environmental Health Engineering, Institute of Industrial Ecological Sciences, University of Occupational and Environmental Health, Japan.

We manufactured 10 WPMs, from WPM-1 to WPM-10. In the preliminary operation check, WPM-3 had several data interruptions, which appeared to be a communication failure related to the BLE. Therefore, the experiment verified nine of the WPMs, excepting WPM-3, using a dust exposure apparatus. Figure 3 shows a schematic diagram of the dust exposure apparatus, the arrangement of the WPMs in the chamber of the apparatus, and the actual measurement images.

After the WPMs were set in the chamber, the dust concentration was measured by diffusing polystyrene latex (PSL, Thermo Fisher Scientific Inc. MA) standard particles muddled liquid into the chamber using a nozzle (compressor) type glass nebulizer with an air flow rate of 30 l/min. We conducted three dust concentration measurement experiments using standard \(\varphi 0.6 \mu m\) particles (Part number; 3600A, Nominal size: 0.600\(\mu m\), Guaranteed average size: 0.596\(\pm 0.006 \mu m\), Particle concentration: 1%, Material: Polystyrene), standard \(\varphi 1.0 \mu m\) particles (Part number, 3600A; Nominal size: 0.600\(\mu m\); Guaranteed average size: 0.596\(\pm 0.006 \mu m\); Particle concentration: 1%; Material: Polystyrene), standard \(\varphi 1.0 \mu m\) particles (Part number, 4009A, Nominal size: 1\(\mu m\); Guaranteed average size: 0.994\(\pm 0.021 \mu m\); Particle concentration: 1%; Material: Polystyrene), and standard \(\varphi 2.5 \mu m\) particles (Part number, 4025A; Nominal size: 2.5\(\mu m\); Guaranteed average size: 2.504\(\pm 0.025 \mu m\); Particle concentration: 0.5%; Material: Polystyrene). We fed these standard particles, diluted with approximately 10 ml of distilled water, separately into the nebulizer and diffused them into the chamber to measure the dust concentration. We cleaned the apparatus before each of the three tests and ensured that there were no previous particles left in the chamber. A drop of standard \(\varphi 0.6 \mu m\) particles muddled liquid was placed into the nebulizer and the dust concentration in the chamber was measured for approximately 27 min. A drop of standard \(\varphi 1.0 \mu m\) particles muddled liquid was placed in the nebulizer and the dust concentration was measured for approximately 16 min. Two drops of standard \(\varphi 2.5 \mu m\) par-

![Figure 2. Drawing of the wearable attachment for the wearable particle monitor (WPM) (left) and an image of it being worn (right).](image-url)
particles muddled liquid were placed in the nebulizer, and after 8 min of measurement, four drops of the same standard particles muddled liquid were placed in the nebulizer, with the dust concentration measured for approximately 17 min.

In parallel with the WPM measurement, the dust concentration (counts per minute (cpm)) in the chamber was measured using an airborne particle counter KC-52 (Rion Corporation, Tokyo, Japan). The measurement interval of the KC-52 was set to 60 s. The data measured by the WPM were recorded in the smartphone application. We used a ZenFone 2 Laser ZE500KL (ASUSTeK Computer Inc., Taipei) with Android 5.0.2 (Google LCC, CA). After excluding the 1-s values of the WPM that exceeded 999, the relative values of dust generation were defined as the value obtained by converting all 1-s values of the WPM into the arithmetic mean value for every minute. We also confirmed the correlation between the values of KC-52 and of each WPM measured by the dust exposure apparatus using Spearman’s rank correlation coefficient and discrepancies among the values of each WPM using the Kruskal–Wallis test according to each standard particle.

**Usability assessment of dust generation measurement in outdoor workplaces using the WPM**

We measured the relative values of dust generation in an outdoor work environment using the WPM and obtained the location information during the WPM measurement. We evaluated the dust emissions by combining the location information and measured values of the WPM.

**Procedure for the measurements of dust generation in outdoor workplaces using WPM**

We measured the dust-generating dust using six WPMs while driving slowly around outdoor workplaces. WPMs were worn by three researchers on their upper arm. The measurers drove in a vehicle with the windows fully open (one driver, one passenger in the front seat, and one passenger in the rear seat) at a speed.
of approximately 10 km/h around the outdoor dust-generating workplaces; the measurement duration was 60 min. After the measured WPM data values were recorded in the smartphone application, the relative value of dust generation was calculated.

**Setting and method of obtaining location information during WPM measurement**

We conducted measurements in January 2020 at a steel-related enterprise in Fukuoka Prefecture, Japan, where many workers engage in dust-generating work outdoors. The weather on the day of the experiment was sunny, the wind speed was 1.9–2.4 m/s, and the temperature was approximately 11.0 °C. To evaluate the dust emission situation in outdoor workplaces, it is necessary not only to obtain information on the relative values of dust generation in the work environment but also to obtain accurate location information of the work environment. The Global Positioning System (GPS), a satellite-based positioning system, was developed by the U.S. Department of Defense (DoD) and is used widely in outdoor environments [21, 22]. As an example of investigation using GPS, research was done to understand the air dose rate distribution of radiation after the accident at the Fukushima Nuclear Power Plant [23, 24]. We referred to this report in our study. We used ZweiteGPS (Senjyusha Co., Ltd., Tokyo), which is a GPS-based location measurement application for smartphones that facilitates recording the time, longitude, and latitude. We used an iPhone 7 with iOS 13.3 (Apple Inc., CA). On the day of the experiment, one researcher measured the relative values of dust generation using the WPM and obtained the location information using ZweiteGPS.

**Construction of the heat map of dust generation**

The ZweiteGPS was set to “walking” for “the means of transportation,” “1 sec” for “logging,” and “maximum accuracy” for “the degree of positioning accuracy.” After the measurements were completed, the time, longitude, and latitude data were exported in comma-separated values (CSV) format for tabulation. Based on the longitude and latitude data for each second, the positions of the researcher at each time (in 1-sec units) during the experiment were plotted on a map to depict the movement of the WPM measurement position. The map used for plotting the location information was modified partially to avoid identification of the enterprise that collaborated in the research. To create a heat map of the dust generation described below, the mean values of longitude and latitude of each second for one minute were calculated and used as the longitude and latitude of the survey points. A heat map of the dust generation was created using Microsoft Excel 2016 MSO (16.0.13029.20232) (Microsoft Corporation, Wash. D.C.), using the measured values of the WPM and the longitude and latitude values of each measurement point. The heat map was created manually, including determining the influence range and providing shade, for the purpose of visualizing the relative abundance in the range of measurements but not for considering the health effects of exposure.

**Results**

**Measurability of WPM**

The measured values of the WPM were well consistent with the measured values of the KC-52, and the trends were generally similar (Figure 4). A strong correlation was observed between the values of the KC-52 and the values of each WPM. No correlation was found in the case of four WPMs in the experiments using standard φ1.0 μm particles (Table 1).

There was no significant difference between the WPMs in the standard φ2.5 μm particles (P=0.099), but there were significant differences between the WPMs in the standard φ0.6 μm particles (P<0.001) and the standard φ1.0 μm particles (P<0.001). In the experiments using standard φ0.6 μm particles, the relative values of dust generation measured by WPM-2, WPM-5, and WPM-1 were higher, while those by WPM-4 and WPM-10 were lower. Conversely, with standard φ1.0 μm particles, the dust levels measured using WPM-1, WPM-2, and WPM-5 were higher. As the measured values of the WPMs increased, the discrepancy among the devices also increased (Figure 4).

**Evaluation of measurement effects due to the six WPM wearing states**

The highest mean measured value in the six WPM wearing states was 12.59 for the WPM wearing state with a wearable attachment in the face side area, and
Figure 4. Measurement verification of wearable particle monitor (WPM) by the dust exposure apparatus. The standard particles were polystyrene latex (PSL) particles, and the muddled liquid particles were diffused into the chamber using a nebulizer. The number following "WPM-" at the bottom of the image is the WPM device number.

Table 1. Spearman rank correlation coefficient ($\rho$) and P-value ($P$) between the values of KC-52 and each Wearable Particle Monitor measured by the dust exposure apparatus

| Standard $\phi$0.6 $\mu$m particle | Standard $\phi$1.0 $\mu$m particle | Standard $\phi$2.5 $\mu$m particle |
|-----------------------------------|-----------------------------------|-----------------------------------|
| KC-52                            | KC-52                            | KC-52                            |
| \(\rho\)                         | \(P\)                            | \(\rho\)                         | \(P\)                            | \(\rho\)                         | \(P\)                            | \(\rho\)                         | \(P\)                            |
| WPM-1                            | 0.91                             | <0.001                           | 0.49                             | 0.018                           | 0.93                             | <0.001                           |
| WPM-2                            | 0.97                             | <0.001                           | 0.47                             | 0.033                           | 0.92                             | <0.001                           |
| WPM-4                            | 0.98                             | <0.001                           | 0.59                             | 0.003                           | 0.93                             | <0.001                           |
| WPM-5                            | 0.99                             | <0.001                           | 0.65                             | 0.001                           | 0.82                             | <0.001                           |
| WPM-6                            | 0.96                             | <0.001                           | 0.06                             | 0.797                           | 0.97                             | <0.001                           |
| WPM-7                            | 0.79                             | <0.001                           | 0.09                             | 0.685                           | 0.89                             | <0.001                           |
| WPM-8                            | 0.94                             | <0.001                           | 0.19                             | 0.380                           | 0.94                             | <0.001                           |
| WPM-9                            | 0.96                             | <0.001                           | 0.18                             | 0.410                           | 0.97                             | <0.001                           |
| WPM-10                           | 0.94                             | <0.001                           | 0.44                             | 0.035                           | 0.98                             | <0.001                           |

the lowest mean measured value was 10.39 for a WPM without a wearable attachment in the face side area, with a range of 2.2

**Distribution of the relative values of dust generation using WPMs in outdoor workplaces**

The relative values of dust generation of six WPMs in outdoor workplaces of a steel-related enterprise were measured, and the passage points were recorded by the researcher (Supplementary Figure 1). The map and trace of the workplaces by Global Navigation Satellite System (GNSS) and the heat map of the relative values of dust generation that was created by integrating the map, trace, and relative values of dust generation in workplaces are shown in Figure 5.

**Discussion**

Regarding the measurability assessment of the WPM, we found that the measured values of the WPM closely followed the measured values of the KC-52, with generally high correlations. The measurability of the same model of a PM sensor was reported in a previous study [25]. Although the conditions were different from those of this study, the measurability of this sensor was confirmed in a general atmospheric environment [25]. Considering the purpose of the WPM, i.e., overviewing the dust generation status in the work environment or the dust exposure status of dusty workers, we believe that the WPM has certain measurability and is consistent with the purpose of its use.

We detected a statistical discrepancy in the measured values among the WPMs, however, and previous studies have reported limitations in the accuracy of the instruments [26, 27]. In the evaluation of the measurability of the WPMs in this study, the variability of the measured values of the WPMs increased under high dust concentration. Since only three types
Supplementary Figure 1. Relative values of dust generation of six wearable particle monitors (WPMs) and the passage points in outdoor dust-generating workplaces of a steel-related enterprise.
of standard particles, namely, $\phi 0.6 \, \mu m$, $\phi 1.0 \, \mu m$, and $\phi 2.5 \, \mu m$, were measured in this study, it is possible that the WPM might not be capable of measuring smaller-sized particles sufficiently. WPMs cannot accurately measure the amount of dust and should only be used as a reference to judge whether the dust generation is high or low. We also observed that the WPMs showing high relative value of dust generation and those showing low relative value of dust generation switched each time they were used. Although we do not know the cause of this phenomenon, solving this problem by measuring the sensitivity of each WPM and calibrating the devices may be difficult. We believe that the WPM measurements could be somewhat inaccurate and inconsistent.

In our experiments in the chamber, we observed transient and unusually high relative values of dust generation measured by some WPMs. We believe that these problems were caused by the wireless communication, since these did not occur with the cable-connected WPM with smart phones or in outdoor measurements with several devices. Noises could easily have caused communication failures in a laboratory environment with many other facilities. Furthermore, communication collisions and congestion may have occurred because the nine devices were communicating simultaneously. Additionally, multiple pieces of data may have been aggregated into a single file, which was then received by the smartphone. To be suitable for personal exposure measurements, which require strict accuracy, the WPM’s performance evaluation of the PM sensors and modification of device calibration must be improved [28, 29].

As discussed, we measured the relative values of dust generation using WPM and location information using GPS during our measurements in outdoor dust-generating workplaces. By combining the measured values of the WPM and GPS location data, we were able to create a heat map of the distribution of relative values of dust generation and visualization of the distribution in the workplace. This technology facilitates identifying work areas with relatively high values of dust generation in outdoor workplaces. Our methodology enabled the identification of work areas where measures to prevent dust emissions or to reduce dust exposure are necessary.

The relative error of the PM sensor installed in the WPM was a maximum of ±15%; therefore, a difference of approximately 3.0 may occur in this experimental environment. The range of the mean measured values of the WPM was less than 3.0. We think that there could be no effect on the measurement via the
WPM by both the wearable attachment for the WPM and the area where the WPM is worn.

We were unable to conduct measurements around the entire workplace owing to the limitation of traveling by car. Conducting measurements on foot would enable measurements of the entire workplace and evaluation of the distribution of dust generation in more detail. Repeated measurements and accumulation of data would also enable us to distinguish work areas with chronically high dust generation, temporarily high dust generation, and areas where workers are exposed to a lot of dust. Such information could lead to the implementation of specific measures to mitigate dust emission and exposure.

There are some strengths in the usability of the WPM for occupational fields. It is easy to wear the WPM because it is compact and lightweight. It can display relative values of dust generation in real-time and in an easy-to-understand manner. The instrument can be used for brief risk analysis related to dust exposure in enterprises and for identifying new risks in outdoor dust-generating workplaces, as dust measurements are not typically conducted in outdoor work environments in Japan. Dust generation measurements could be conducted easily for temporary or short-term dusty work (e.g., equipment maintenance, equipment troubleshooting, and the like). Using the WPM in workplaces with moving dust emission sources, which are not subject to work environment measurements, could contribute to improving the work practice and environment.

Limitation and future direction

This study has a few limitations. First, the WPM used in this study is a prototype. If an improved WPM is mass-produced in the future, it will be necessary to verify whether the same results can be obtained with the mass-produced machine.

Second, the accuracy and reliability of the PM sensors built into the WPM are insufficient, and a standardization and certification scheme for low-cost PM sensors has not been established. The measured values output by the WPM are for reference, and they cannot be used as an alternative method of measurement, which requires strict accuracy as “work environment measurements” or “personal sampling,” required by laws and regulations [30]. It is also not appropriate to treat the results measured by the WPM as the results of “work environment measurement” or “personal sampling.” These points may be resolved if more high-performance, smaller, and low-cost PM sensors are developed and a standardization and certification scheme for them is advanced in the future.

Third, the findings of this study will be affected by weather conditions. On the day of the experiment, weather conditions were relatively calm, with clear skies and no high wind speed, but when it is raining, the entire outdoor workplace would become wet and dust emission would be temporarily suppressed. When it is windy, the WPM could detect dust generated in distant areas and transported by the wind. It has also been reported that the value of dust concentration measured by PM sensors tends to be overestimated, given their ability to detect visible light, because humidity affects the increased moisture content of particles [31, 32]. We have not yet verified the effectiveness of the WPM in such different weather conditions, and further study is, therefore, necessary.

Fourth, there are issues regarding the accuracy of the location information. GNSS is difficult to use indoors because it cannot receive satellite signals. The positioning error may be as small as approximately 10 m, even outdoors, depending on the operating environment of the device [33]. In this study, we converted the location information acquired every second to the position information every minute. Even if we used the location information acquired at shorter intervals, it would be technically difficult to identify the exact position owing to the occurrence of errors, making it difficult to identify the exact location information of a dust source in a place where the possible dust sources are concentrated in a small area. The error could be reduced by using a submeter class positioning augmentation service, such as the Quasi-Zenith Satellite System (QZSS) [34, 35], but the smartphone used in this study is not compatible with that system. Further verification using these services should be considered in the future, and technologies such as beacon and Wi-Fi round trip time (RTT) could be applied for indoor location positioning.

We believe that using WPM could improve workers’ awareness of the need for prevention from dust
exposure. It has been reported, for example, that the newly developed Helmet-Cam technology developed by the U.S. National Institute for Occupational Safety and Health has been useful for assessing dust exposure of workers and is beneficial for safety meetings and other presentations [36]. As the relative values of dust generation can be verified in real-time, workers can proactively wear proper personal protective equipment and review their working procedures. Regarding occupational health education, we believe it would be effective to present our method and the actual heat map results to workers exposed to dusty environments. We will continue to study the creation of effective and useful heat maps based on the opinions of experts regarding occupational health and work environments and actual dusty workers, as well as the results of future surveys.

**Conclusion**

In this study, we constructed a WPM and investigated its usability in outdoor dust-generating workplaces. We found that the instrument was suitable for overviewing the dust emission status of the work environment and the dust exposure status of workers. The methodologies in our study could be applicable to the occupational field of WPM.

**Acknowledgment**

We appreciate the cooperation of Mr. Norihisa Kosukegawa from Yaguchi Electric Co., Ltd., in manufacturing the WPM. We would like to thank Editage (www.editage.com) for English language editing. We would also like to thank all the participating companies, participants, and staff members.

**Funding**

This study was funded by the Industrial Disease Clinical Research Grants (180302-01).

**Conflict of Interest**

Yo Ishigaki is a part-time director of Yaguchi Electric Co., Ltd. The other authors have no conflicts of interest to declare regarding this study.

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