

Field evaluation of measuring indoor noise exposure in workplace with task-based active RFID technology

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Received 6th October 2009, Accepted 27th November 2009

First published as an Advance Article on the web 20th January 2010

DOI: 10.1039/b920684a

This paper describes the research using RFEMS (Radio Frequency Identification Exposure Monitoring System), which is designed by applying the task-based active RFID (radio frequency identification) technology, to measure the indoor noise exposure dose in a workplace. The RFEMS and sound level meter are mounted on the vests of eight workers to carry out on-site field test by monitoring the time activity pattern (TAP), and the noise dose level exposed by the workers. The data are recorded and instantaneously transmitted to a computer to be saved in the server and later compared to those obtained using the standard method. The results that have a 0.909 correlation coefficient (R^2), and 1.64% average measure error confirm the accuracy of using RFEMS for monitoring TAP. Additionally, the combined use of RFEMS and sound level meter leads to the development of a semi noise dosimetry (SND), a real-time electronic indirect noise dosimetry (REIND), and an equivalent electronic recording indirect noise dosimetry (EEIND). The results obtained using these three devices are well correlated with the results monitored by using a PND (personal noise dosimetry) with correlation coefficients (R^2) of 0.915, 0.779 and 0.873, respectively. The errors of noise dose expressed in TWA (time weight average) for these three methods are 0.81, 1.57 and 1.23 dBA, respectively; they are well within the general errors of the average dosimetries. These observations indicate that the RFEMS developed in this research is applicable for conducting task-based measurements of indoor noise. It uses a relatively inexpensive sound level meter to measure the noise exposure doses that are comparable to those obtained with a standard dosimetry in addition to monitoring the worker's time activity pattern. The findings will assist in studying the source of long-term noise exposed by workers, and hence this device is a valuable tool for tracing and monitoring long-term noise exposure with reduced manpower requirements.

Introduction

The exposure occurs when a person comes into contact with a pollutant at a particular instant of time if the pollutant and the person are present at the same location. Hence, the exposure becomes the intersection, or joint occurrence, of two events: the person is present, and the pollutant is present as well. The exposure assessment can be done by using either direct approach or indirect approach. The former is to detect directly the human exposure dose whereas the latter measures the microenvironment contaminant concentration and human exposure time for estimating the exposure dose.¹ Hence, the exposure assessment depends on a complete record of the duration of exposure to assist in tracking the exposure source. Results of previous

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Environmental impact

The exposure assessment depends on a complete record of the duration of exposure to assist in tracking the exposure source. In recent years, much effort has been directed toward improving the direct approach for better evaluation of the exposure dose but the result fails to provide explanations on source and cause of exposures. Our research team has successfully developed an automatic system to monitor the time activity pattern and record the indoor noise level. The results indicate the application will also reduce the equipment cost, and relieve the limitations of manpower needed for conducting further evaluation of noise exposure. Using the method recommended will assist in strengthening the research ability to study and analyze worker's operational mode, and the management of noise pollution.

studies^{2,3} show that although the direct approach may accurately provide the total exposure dose for a person during the study period, this approach will not reveal the exposure concentration or intensity, location, and exposure time. In recent years, much effort has been directed toward improving the direct approach for better evaluation of the exposure dose but the result fails to provide explanations on source and cause of exposures.

Indirect approach has distinct advantages over direct approach in that the former provides a more direct understanding of the sources of high exposure, and therefore helps target effective exposure control interventions. This approach is easy to implement in addition to providing time-dependent activities so that the researchers understand the source of exposure. Hence, it has been adopted by numerous researchers for evaluating exposures to chemical pollution^{4,5} and noise.^{6,7} However, the TAP (time activity pattern) data are often obtained using the manual questionnaire survey method, or through time activity diaries that are often erroneous or lack accuracy. Hence, the results thus obtained do not reflect the real exposure event.^{8,9}

Under the auspices of Institute of Occupational Safety and Health (IOSH), Council of Labor Affairs, Taiwan, our research team has successfully developed an automatic system to monitor TAP and record the indoor noise level. The field study of using the pilot system for evaluating the noise exposure dose in a steel manufacturing plant has been carried out. This system is expected to provide researchers for obtaining appropriate data to perform complete analyses of the indoor noise exposure.

Currently used methods and their limitations

Direct approach

In the conventional direct approach, a person carries a sampling instrument to monitor the level of exposure, and the cumulative exposure over a period of time is calculated to result in the integrated exposure. This method is regarded as the “golden standard”.^{10–12} Its major advantage is that the results closely represent the exposure; the disadvantage is that only the total exposure dose is obtained. Three types of instrument are used in the direct approach; they are active sampling train, passive monitor, and direct reading instrument. This method is usually very expensive^{5,10} and time-consuming for instrument purchase and preparation, sample collection, and result analyses. Because the direct approach has often been questioned for lacking efficiency and cost-effectiveness, it is only used to evaluate the noise exposure for a smaller population. If used for a large-scale exposure assessment survey, a small group of individuals is randomly selected from a large population for conducting the exposure evaluation. The results thus obtained may excessively deviate from the real situation.¹³ Hence, some researchers suggest that the TAP survey be conducted along with the use of direct reading instruments.³

Indirect approach

Ott (1985) proposed a modular approach to estimate the total dose exposure by summing up the products of the local contaminant concentrations and the exposure times.¹ In this research, the TAP for a person under a microenvironment is complemented with environmental sampling to yield the

contaminant concentration for calculating the total exposure of an individual using eqn (1):

$$E_i = \sum_{j=1}^J C_j \times T_{ij} \quad (1)$$

E_i : the total exposure for person i in a certain duration

C_j : local contaminant concentration in microenvironment j

T_{ij} : time that person i stays in microenvironment j

J : cumulative stay for person i in microenvironment j

In the indirect approach, environmental sampling is easier than personal sampling if representative microenvironments are selected. Because individual workers are not involved in the sampling, the sampling cost can be greatly reduced. Additionally, the time activity in the questionnaire survey method is easy to acquire inexpensively, thus, this method can be applied to a large population.¹⁴ However, the errors of personal memory, the cooperative attitude of those interviewed, and inappropriate design of questionnaires lead to inaccurate results with uncertainty and poor quality. If the results thus obtained are used for evaluating personal exposure, the final results will be much different from the actual situation.⁸ Additionally, using environmental sampling to represent personal exposure doses will have discrepancies between the sampling position and the personal exposure position.¹⁵

During the exposure period, the potential exposure dose for a person is the total summation of all contaminants inhaled. Since the contaminant does not exist in the environment continually, the accumulative exposure will yield the total exposure dose. If differentiation of the environment is carried out, and the time for a person steps into and out of the environment is instantaneously recorded, complete information on the exposure concentration duration and exposure time can be obtained for accurately evaluating the exposure dose for the person in question. Hence, how to accurately observe and record the position and duration of the exposure is the problem that recent researchers are trying to resolve.^{8,16}

The source

Many methods have been developed over the past few years to investigate workers' operating situations, to explore the causes of workers' pollutant exposure, and to automate the collection of workers' time/activity data. These methods include VEM,¹⁷ GPS,¹⁸ IR-tags¹⁹ among the many other tracking systems.²⁰

VEM is another method accepted by practitioners in various domains. It is a monitoring instrument that combines contamination data with video imaging of the worker's activities. The exposure data are acquired in real time and correlated with the videotape records. This technology can simultaneously record the exposure data for individuals and their associated activities they are performing. The processing of VEM data is, however, very time consuming to correlate the exposure readings with locations in addition to being subjected to some degree of human interpretation errors. The effort required increases proportionally with respect to the number of workers being monitored.

The GPS technology is a powerful locating method that is used widely for locating or tracking a person or worker. The

technology is mainly for outdoor applications, because many indoor spaces are out of reach of the GPS service.

For indoor applications, several methods have been proposed or developed for tracking a person's location and behavior. For example, IR-tags, although limited by dead space and scattering, are most applicable in smaller-scale workplaces for tracking mobile workers. Other tracking systems, such as those using color image processing, have limitations because they are not reliable when used for detecting or locating human figures.^{21,22} In addition, these systems suffer from complicated color distributions of captured scenes with variable lighting conditions. Furthermore, the time/event record (TER) system is a portable time activity recorder that is operated manually,²³ for example, pressing a particular button to record their event and location to trace and identify the user. Mistakes and errors often arise from the operator's omitting or forgetting to perform the operation. Additionally, the manual operation interferes with the workers performing their tasks. Although the shadow sensor can detect ceiling space to distinguish the locations of workers in various environments, such as outdoors (>3.5 m), indoors (1–3.5 m), or next to a vehicle (<1 m), this approach is not very useful for distinguishing the various ceiling spaces in microenvironments.²⁴

Methods for monitoring noise and their limitations

The scope of noise measurement includes environmental noise measurement, traffic noise measurement, aviation noise measurement, workplace environmental measurement. For the workplace environmental measurement, the sound pressure level and personal dosimetry are evaluated to assure that they meet the legal limitations. The measurement can be done using two methods: environmental sampling and personal sampling.

(a) Environmental sampling. The workplace is marked by grid lines with 3–5 m between two adjacent lines. Dosimeters of Type 2 or above are installed 1.2–1.5 m above ground at the grid line intersecting points; the results are plotted on the noise map. The operating time of a worker can be included to calculate the total exposure dose for the worker. This method has been used in many studies to cope with the time activity diaries for estimating the individual's total exposure dose.^{25–28}

(b) Personal sampling. The worker's noise exposure measurement is usually carried out using a noise dosimeter for understanding whether the worker's noise exposure dose exceeds 100%.²⁹ Although this instrument is simple to operate, it only measures the total daily exposure for the worker without providing any detailed information on the source of noise such as the location of exposure or duration of exposure. The noise exposure dose reveals whether the noise level exceeds the legal limitation, but the researchers cannot further understand the details on the exposure location and the operational conditions for the exposed worker.³⁰ If the long-term information on the duration exposed to noise for a worker is not available, the diagnosis and improvement of the worker's chronic permanent threshold shift (PTS) will be very limited. Identifying the source of noise is an important step prior to starting a noise control project. The worker TAP is of primary importance for

understand his activity; lacking accurate TAP information causes difficulties in implementing the noise improvement project.

A proposed better solution

Under the support of the Institute of Occupational Safety and Health (IOSH), Council of Labor Affairs, Taiwan, our research team has developed RFEMS (Radio Frequency Exposure Monitoring System) that is based on the Active RFID (Radio Frequency Identification) technology for solving the problem of long-term noise exposure for workers at the workplace. This system can be used for 32 work areas or micro-environmental spaces for locating 256 workers simultaneously. The radio frequency and signal intensity can be adjusted to suit indoor operations in rooms of various sizes to automatically record the worker's activity every second. Additionally, if used with physical and chemical monitors, this system will provide Ethernet functions to collect and transmit the worker's real-time location, stay time, and exposure intensity so that the research can grasp the accurate information for conducting a better evaluation.

In this research, RFEMS is used with the sound level meter, which has been well developed using mature technology, to carry out systematic and accurate measurement for evaluating the applicability of the proposed new monitoring system by monitoring the worker's stay location, stay time and noise exposure dose.

Methods

RFEMS Instruments

Our research team applied the nRF24E1 transceiver (2.4 GHz, the size is 6 mm × 6 mm × 0.7 mm, Nordic Semiconductor), and Siteplayer web server (30 kbits flash memory, the size is 3.3 cm × 3 cm × 1.6 cm, NetMedia Inc.) to complete the design of RFEMS with an integral configuration. The RFEMS instrument consists of an exposure monitoring subsystem, and a data storage-analysis subsystem. Fig. 1 shows the schematic overview of system configuration.

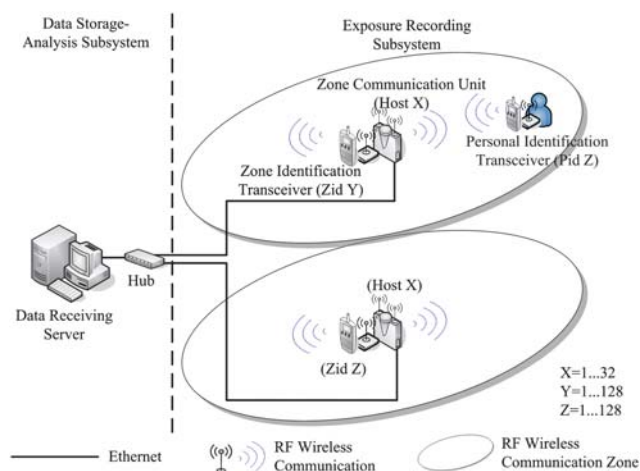


Fig. 1 Schematic overview of the RFEMS architecture.

Exposure monitoring subsystem. The subsystem includes zone communication unit (Called Host), personal identification transceiver (Called Pid), zone identification transceiver (Called Zid), environmental sensing unit, and power supply unit.

a) Zone communication unit (Host): The Host is approx. 16 cm × 11.6 cm × 4 cm; each weighs about 400 g. It is composed of zone transmission module (ZTM) and zone reception module (ZRM). ZTM takes charge of emitting wireless zone communication code (Called zone number) and time sequence. Pid and Zid receive the zone code and time sequence transmitted from ZTM and integrate the data. These data and additional worker communication code, and environmental monitoring data form a wireless data package are transmitted to ZRM. The wireless data package consists of four data components: the worker communication code (“worker number”), the zone communication code (“zone number”), the time sequence, and the environmental monitoring data. Once receiving the Pid and Zid data package, ZRM further transmits the data package through a serial connection (RS-232) to the Siteplayer web server that is linked through LAN (local area network) to the data-receiving server where the data are stored and analyzed. The exposure storage-analysis software is used to analyze the zone communication code, worker communication code, environmental monitoring data, and server system time, and save the exposure monitoring data.

b) Personal identification transceiver (Pid): The Pid is a small-sized transceiver with active RFID measuring approx. 3.5 cm × 8 cm × 1.8 cm and weighing about 60 g. It is an essential unit for providing the data of the working location, time spent and exposure monitoring data for workers. This device can be integrated with a variety of physical or chemical sensing instruments such as noise meter or gas sensor. Our team have successfully integrated the sound level meter (TES-1350A), and gas sensors (Figaro TGS-822), which may be physical or chemical sensing instruments with analogy signal output terminal, into the Pid receiver.

c) Zone identification transceiver (Zid): The Zid is not an essential unit; it is used for only surveying the TAP of worker. The Zid is capable of integrating with various direct reading instruments for microenvironment. As the functions of

monitoring and transmitting data are concerned, Zid is identical to Pid because both are sensing real-time environment information. The difference is that Zid is connected to the Host whereas Pid is mounted on workers.

d) Environmental sensing unit: The environmental monitor units include sound level meter and noise dosimeter. (1) Sound level meter: The sound level meter available on the market (TES-1350A, 24 cm × 6.8 cm × 2.5 cm, IEC 651 Type 2, manufactured by TES Electrical Electronic Corp.) is used; it has A Weighting and C Weighting with fast and slow dynamic responses. The unit is not expensive (about US\$ 80), and is readily available. It is powered by DC with output connections to immediately transmit the analogy noise information. (2) Noise dosimeter: The noise dosimeter, which is available on the market (TES-1355, 10.6 cm × 6.4 cm × 3.4 cm, Type 1), is manufactured by TES Electrical Electronic Corp. It is capable of storing 5 sets of data including dose, TWA, and exposure time, and outputting the data through RS-232 interface to a personal computer for analyses. Photographs of the RFEMS exposure monitoring subsystem are shown in Fig. 2.

Data storage and analysis subsystem. The subsystem includes data-receiving server and exposure storage-analysis software,

a) Data-receiving server: Pentium 4 2.0 G or higher level CPU and 256MB or higher level is recommended for data-receiving server. The recommended operating system includes Windows 2000, Windows XP or Windows 2003 and above to satisfy the optimum efficiency.

b) Exposure analysis software: The software developed in Visual Basic 6.0 with the functions for receiving the package, and then recording the server system-time, zone number, worker number, personal environment monitoring signal, and zone environment monitoring signal is used. The major functions of the software installed on the monitor include primary control panel, activity zone for the workers, and environmental monitoring panel. The primary control panel is frequently used for setting monitoring object, displaying system-time, setting monitoring parameters and monitoring frequency, and displaying real-time network package. Individual worker's activity and exposure monitoring recording panel can be switched to monitoring menu of the worker in real-time mode so that the location of worker can be immediately obtained with simultaneous zone exposure monitoring values. The monitoring data can be immediately stored in data-receiving server for data analyses later by researchers.

Operating procedure

The operating procedure of RFEMS is shown as follows:

a) The process of determining the workers' location and residence time: first, the researchers need to define the scope of several communication zones according to the features of the workplace (microenvironments), and setup a zone communication unit (known as the Host), with a exclusive code and wireless communication range covering the whole zone. Next, the workers wear the Pid vest with exclusive codes and wireless communication function. Moreover, if researches want further monitoring information from various sensors, the Zid can be integrated into the zone communication unit for delivering

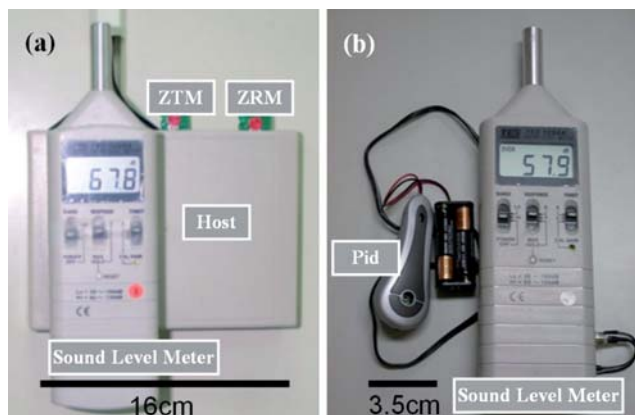


Fig. 2 Photographs of the RFEMS exposure monitoring subsystem: (a) Host and environmental sound level meter; (b) Pid and personal sound level meter.

monitoring information in real-time mode. When a worker wearing the Pid vest steps into the communication zone of a Host, the Pid will launch a two-way communication with the Host. It receives the exclusive code signal (zone number) and time sequence from ZTM and the zone number and time sequence from the ZTM, integrated the data and additional exclusive code signal (worker number) and environmental monitoring data into a wireless data package, and emitted the package to the ZRM. The Host transforms the signal from the Pid into a data package and then transmits it through the Site-player web server. During this process, the system can identify the status of workers who have stepped into the zone, and their time activity and exposure data including worker number, zone number, personal and zone sensing data of environment that will be transmitted to the data-receiving server simultaneously.

After a worker steps into the communication zone, the system will continually transmit his time activity and exposure data for each second until the workers move into the next communication zone. The personnel identification transceiver (Pid) also keeps the two-way communication with the communication unit in the next communication zone (Host) so that the system can identify the status of the worker when he steps into the next zone, and the time status of his exposure data.

b) The process of monitoring data transmission: the Host is able to transmit the data collected from Zid or Pid to the data-receiving server in real-time mode for analysis with UDP (User Datagram Protocol). As a result, the Host and data-receiving server can easily transmit and record the exposure monitoring data of workers.

Field experiments

The field test was carried out in a steel manufacturing plant in southern Taiwan. RFEMS was installed at the bar-mill production line for conducting the pilot test. The test lasted for four days with eight workers who are actually working at the production line. There are eight microenvironments established according to the actual operation of the production line so that the feasibility of understanding the workers schedule, mode of activity and the exposure noise dose can be studied. The procedures for conducting the field test are explained as follows:

1. Pre-testing the time activity recording function

Observation of the workers' activity by human observer was conducted as the standard method. The activity was also observed and recorded using RFEMS, and questionnaire along with observation on the activity of the workers including identification number, time and location of stay. All workers involved in the study wore Pid vest, and the Pid kept communicating with the Host during the experimental period to instantaneously transmit data on time and location of their stay to complete electronic TAP records. Additionally, the researcher also manually tracked and observed the time each worker entered the microenvironment and their stay time to complete the record by human observation. Finally, during the lunch hour and before the end of the working day, time activity questionnaires were distributed to the workers which involved them to select their morning and afternoon activities based on 15-minute

intervals. The above three types of TAP records were then analyzed and compared at the end of the experimental period.

2. Pre-test of the noise exposure dose monitoring

A Personal Noise Dosimeter (PND) (TES-1355) was used as the standard method for verifying the worker's noise exposure dose. The instrument parameters were set using the specifications of the Council of Labor Affairs, Taiwan. The hearing conservation standard includes "A" frequency weighting, slow meter response, a 90-dB criterion level, an 80-dB threshold, and a 5-dB exchange rate. Additionally, the sound level meter (TES-1350A) was installed on each worker, and the center of each microenvironment to monitor the real time sound level exposed by the workers and the micro-environmental sound level. Fig. 3 displays the micro-environmental zones and the instrument. For calculating the noise exposure dose, the personal noise dosimetry was used as the standard method; the results were compared with those obtained using the SND (semi noise dosimetry) and other indirect noise dosimetry for cross comparisons in order to understand the accuracy of RFEMS for monitoring the noise exposure dose. The various methods for calculating the noise exposure dose are explained as follows:

(1) **Personal Noise Dosimetry (PND).** The personal noise dosimetry, which uses the personal noise dose to calculate the noise exposure dose directly, is considered the standard method for evaluating the noise dose expressed in %. The personal noise



Fig. 3 Photographs showing the setup of field RFEMS: (a) the Host location and schematic diagram of the RF communication zones, (b) establishment of Host, Zid, and dosimeter in the microenvironment, (c) the worker vest with personal noise dosimeter, Pid and Sound level meter, dotted lines showing the location of each instrument inside the vest.

dosimetry (%) can be converted into time weight average (TWA) in dBA using eqn (2). The latter is used in this study as the standard for comparing results.

$$\text{TWA} = 90 + 16.61 \log \left(\frac{\text{PND}}{100} \right) \quad (2)$$

TWA: Time Weight Average (dBA)
PND: Personal Noise Dosimetry (%)

(2) Semi noise dosimetry (SND). An inexpensive personal sound level meter mounted on the worker's vest was used in this research to monitor the noise exposure for the worker. The data were transmitted through the RFEMS to the data receiving sever that conforms to the specifications of the Council of Labor Affairs, Taiwan on hearing conservation standard for calculating the noise dose. Since RFEMS immediately transmitted the personal noise data, the personal sound level meter can thus be elevated to have functions of an expensive personal noise dosimetry. The combination of RFEMS and the personal sound level meter is named semi noise dosimetry (SND). The data characteristics of SND are the same as those collected using the expensive personal noise dosimetry but they do not include the time and a worker's stay time. The advantage is that the RFEMS system can be utilized for converting the inexpensive sound level meter into a more expensive noise dosimetry thus the cost for collecting noise data can be greatly reduced.

Using the 5-dB exchange rate, the personal noise intensity ($\text{SPL}_{\text{personal}}$) transmitted for every second can be converted into the allowable stay time for the noise level (T_{personal}) as shown in eqn (3). The calculated T_{personal} based on the data transmitted every second can be used to calculate SND (eqn (4)):

$$T_{\text{personal}} = \frac{8}{2^{\left(\frac{\text{SPL}_{\text{personal}} - 90}{5}\right)}} \quad (3)$$

$$\text{SND} = \sum_{t=1}^{\infty} \frac{t_{\text{personal}}}{T_{\text{personal}}} \times 100\% \quad (4)$$

T_{personal} : Permissible stay time in hours for a worker exposed to the sound pressure level

$\text{SPL}_{\text{personal}}$: Sound Pressure Level in dBA of personal
SND: Semi Noise Dosimetry (%)

t_{personal} : Actual stay time in hours for a worker exposed to the sound pressure level

(3) Indirect Noise Dosimetry (IND). Each microenvironment had one Host installed; the instantaneous noise for each microenvironment was monitored with an environment sound level meter located at the center of each microenvironment. Coupled with the worker's activity records, the system can be developed into an indirect dosimeter. The calculation of IND requires the worker's time activity records (TAR) and the environmental noise monitoring data to determine the micro-environmental location and the noise level (SPL_{zone}) of the microenvironment at each time point for the worker. Using the 5-dB exchange rate, the permissible time (T_{zone}) for the worker to stay in the microenvironment can be calculated based on eqn (5). Eqn (6) can be used to convert t_{zone} into IND:

$$T_{\text{zone}} = \frac{8}{2^{\left(\frac{\text{SPL}_{\text{zone}} - 90}{5}\right)}} \quad (5)$$

$$\text{IND} = \sum_{t=1}^{\infty} \frac{t_{\text{zone}}}{T_{\text{zone}}} \times 100\% \quad (6)$$

T_{zone} : Permissible stay time in hours for a worker exposed to the sound pressure level

SPL_{zone} : Sound Pressure Level in dBA of zone

IND: Indirect Noise Dosimetry (%)

t_{zone} : Actual stay time in hours for a worker exposed to the sound pressure level

Additionally, based on the source of IND data, and sound level data and time activity record (TAR), the sound level data can be classified into real time sound pressure level (SPL) and equivalent Energy Sound level (Leq); the TAR data can be classified as direct observation, questionnaire, and RFEMS. The calculated IND of four different sources of data can be combined to carry out the comparison of six different noise exposure doses. Table 1 lists the data for calculating the various noise exposure doses and their sources:

(a) Personal noise dosimetry, PND: Adopted as the golden standard, and used in this research as the standard for verifying the noise exposure dose.

(b) Semi noise dosimetry, SND: Calculated using the results acquired with a personal sound level meter.

(c) Real-time electronic recording indirect noise dosimetry, REIND: An indirect noise exposure dose calculated using the SPL monitored in individual microenvironment coped with the RFEMS records on time-dependent activities.

(d) Equivalent electronic recording indirect noise dosimetry, EEIND: An indirect noise exposure dose calculated using the equivalent energy sound level (Leq), which is the average of daily overall instant sound pressure level coped with the RFEMS records on time-dependent activities.

(e) Equivalent observation recording indirect noise dosimetry, EOIND: An indirect noise exposure dose calculated using the equivalent energy sound level (Leq), which is the average of daily overall instant sound pressure level, coped with the observation records on time-dependent activities.

Table 1 Noise and activity time sources for six difference noise exposure doses

| Dosimetry | Sound monitoring meter | Sound data character | Time activity data character |
|-----------|--|----------------------|------------------------------|
| 1 PND | Dosimeter (TES-1355) ^a | Real time (SPL) | None |
| 2 SND | Sound Level Meter (TES-1350A) ^a | Real time (SPL) | None |
| 3 REIND | Sound Level Meter (TES-1350A) ^b | Real time (SPL) | RFEMS |
| 4 EEIND | Sound Level Meter (TES-1350A) ^b | Equivalent (Leq) | RFEMS |
| 5 EOIND | Sound Level Meter (TES-1350A) ^b | Equivalent (Leq) | Observation |
| 6 EQIND | Sound Level Meter (TES-1350A) ^b | Equivalent (Leq) | Questionnaire |

^a Personal sampling. ^b Environmental sampling.

(f) Equivalent questionnaire recording indirect noise dosimetry, EQIND: A n indirect noise exposure dose calculated using the equivalent energy sound level (L_{eq}), which is the average of daily overall instant sound pressure level coped with the questionnaire records on time-dependent activities.

Results and discussions

Overview

The feasibility of using RFEMS to automatically monitor the worker activity and noise exposure dose is evaluated by using a pilot RFEMS installed at a bar-mill production line of a steel manufacturing plant in southern Taiwan. The test lasted for four workdays in a 100 m by 40 m room with high temperature (30 °C and above) and noise level (90 dBA and above). The testing site included eight regions of reheating furnace, roughing mill, intermediate mill, finishing mill, staff lobby, office, toilet, and control room. The workers moved around in a 20 m wide area in front of the production line. The noise level was between 85–90 dBA in all regions except the staff lobby and office. During the steel production, the workers moved around in all eight regions. Results of preliminary tests indicate that the RFEMS system is operating satisfactorily during with sufficient power supply to last for the eight-hour working day.

RFEMS will collect the on-site instantaneous sound pressure level data through the zone communication unit (Host), and save the results in the data-receiving server to be retrieved later. Table 2 lists the calculated equivalent energy sound level (L_{eq}) using RFEMS for an eight-hour working day. The noise levels in the production regions of zone A through zone D are above 80 dBA that are hazardous to the workers. In the administrative zones of zone E through zone H, the noise levels are less than 85 dBA that are close to the noise level of a general public place.

Table 2 The equivalent energy sound level (L_{eq}) in the eight microenvironments of the testing site

| Region ID No. | Location | Data Count. | L_{eq} (dBA) |
|---------------|-------------------|-------------|----------------|
| A | Reheating Furnace | 28485 | 89.1 |
| B | Roughing mill | 28536 | 95.3 |
| C | Intermediate mill | 28606 | 89.4 |
| D | Finishing mill | 28608 | 91.2 |
| E | Staff lobby | 28530 | 74.7 |
| F | Office | 28607 | 74.3 |
| G | Toilet | 22625 | 84.0 |
| H | Control Room | 28607 | 70.1 |

Table 3 Noise exposure for the eight workers involved in the evaluation

| Worker ID No. | Worker Position | No. of Data | Dose (%) | TWA (dBA) |
|---------------|-------------------------|-------------|----------|-----------|
| 1 | Finishing mill operator | 26040 | 110.9 | 90.7 |
| 2 | Section Chief | 28080 | 28.29 | 80.9 |
| 3 | Section Chief | 25937 | 31.69 | 81.7 |
| 4 | Mill foreman | 27268 | 86.43 | 88.9 |
| 5 | Finishing mill operator | 27250 | 81.94 | 88.6 |
| 6 | Finishing mill operator | 25213 | 69.05 | 87.3 |
| 7 | Mill foreman | 26335 | 79.79 | 88.4 |
| 8 | Section Chief | 26580 | 57.71 | 86.0 |

Additionally, the noise exposure doses for workers with activities in these eight regions are listed in Table 3. Six of these eight places have TWA greater than 85 dBA with one place exceeding 90 dBA and two places between 80 to 85 dBA indicating that most of the workers need hearing protection.

Result of verification of time activity pattern

Activities of the eight workers in the microenvironments were observed and recorded using the three methods of observation, questionnaire, and RFEMS. The results expressed in percentage of time for the worker staying in each microenvironment are shown in Table 4 and Fig. 4. Using the time activity pattern collected with the observation method as the basis for comparison, the errors are 2.35% for the questionnaire method and 1.64% for the RFEMS method. Fig. 4 indicates that results obtained using the observation and the RFEMS methods have a tendency to be close to each other for workers with major activities in zone D through zone F.

The correlation between TAP results on the percent of time for workers staying in each zone collected using the questionnaire and the RFEMS methods are shown in Fig. 5(a) and Fig. 5(b) with numbers representing the worker's ID number and dashed line indicating the 95% confidence intervals. The correlation coefficient (R^2) are 0.696 for the observation and the questionnaire methods (Fig. 5(a)), and 0.909 for the observation and the RFEMS methods (Fig. 5(b)). The results indicate that using the observation method as the standard method, the error of using the RFEMS method to observe the workers' indoor time activities is 1.64% with 0.909 correlation coefficient (R^2). Thus, the RFEMS results are comparable with the results obtained with the observation method. However, the RFEMS method is superior to the observation method in that the former does not interfere with the workers' activities so that the cost for collecting data collecting is relatively inexpensive. Hence, the RFEMS method is more suitable for conducting long-term studies.

Results of verifying the noise exposure doses

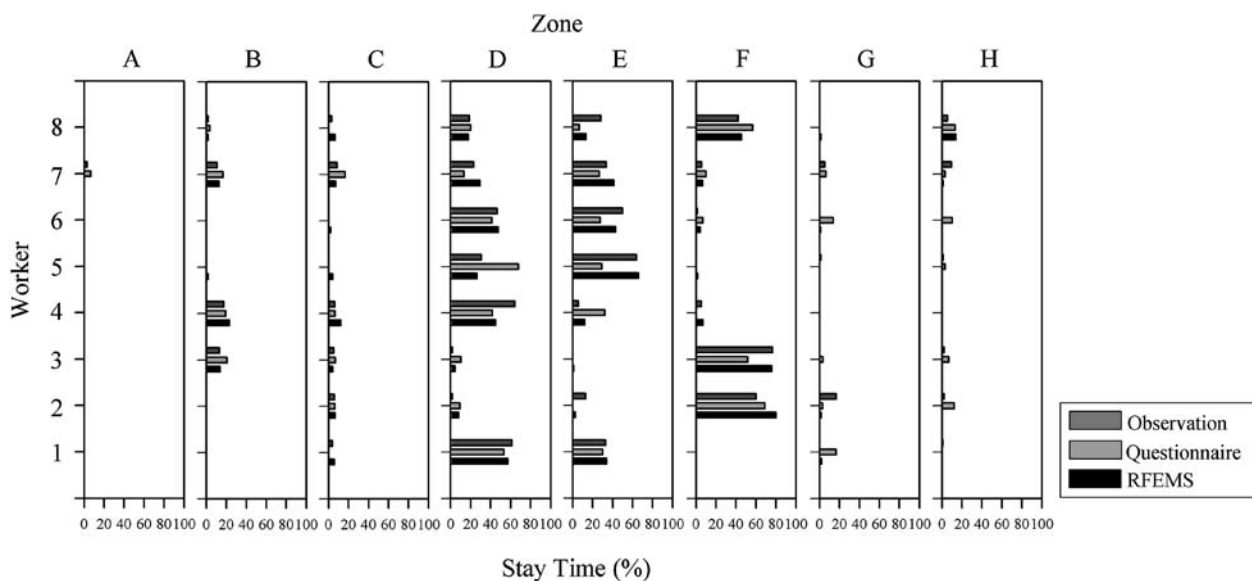
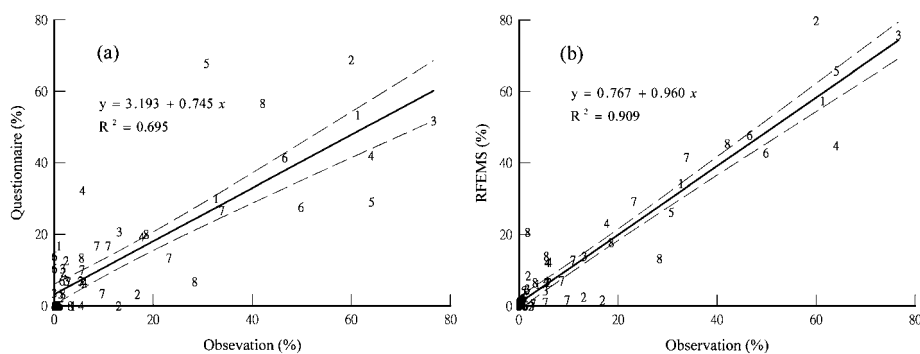
In this study, the worker time activity records were simultaneously collected using the observation, the questionnaire, and the RFEMS methods for evaluating the accuracy of using the RFEMS method. The study involved eight workers to monitor their activities in eight microenvironments. The personal noise dosimetry (PND) is used as the standard method for collecting noise level, and the RFEMS is applied for collecting time activity, regional noise level, and personal exposure data using the SND, the REIND, and the EEIND methods for monitoring noise exposure doses. The observations also included the results on five noise exposure doses, *i.e.* EOIND and EQIND, based on a conventional method of observation for understanding the errors of using the RFEMS methods to record noise exposure dose, and the correlation with the results obtained using the standard method. Hence, the feasibility of using the RFEMS for monitoring indoor noise exposure doses can be evaluated. The results are discussed in the following sections:

1. Semi noise dosimetry (SND). Fig. 6(a) and Fig. 6(b) show the correlation between, and the linear regression of the results

Table 4 Results of time activity pattern (TAP) recorded using the observation, the questionnaire and the RFEMS method

| Zone | No. of Workers | No. of data ^a | Mean time % (SD ^c) | | | Bias (%) | |
|-------|----------------|--------------------------|--------------------------------|---------------|---------------|---------------|-------|
| | | | Observation ^b | Questionnaire | RFEMS | Questionnaire | RFEMS |
| A | 8 | 227880 | 0.54 (0.99) | 0.83 (2.36) | 0.38 (0.37) | 0.30 | 0.15 |
| B | 8 | 228288 | 5.69 (7.08) | 7.51 (9.57) | 6.99 (8.49) | 1.81 | 1.29 |
| C | 8 | 228848 | 4.38 (2.65) | 4.53 (5.88) | 6.08 (2.94) | 0.15 | 1.69 |
| D | 8 | 228864 | 30.98 (24.41) | 32.18 (22.01) | 29.51 (19.11) | 1.20 | 1.48 |
| E | 8 | 228240 | 28.44 (21.84) | 19.03 (14.16) | 26.63 (22.98) | 9.41 | 1.82 |
| F | 8 | 228856 | 23.99 (30.92) | 24.26 (29.41) | 27.54 (34.21) | 0.27 | 3.56 |
| G | 8 | 181000 | 3.16 (5.78) | 5.46 (6.50) | 0.93 (0.76) | 2.31 | 2.23 |
| H | 8 | 228856 | 2.82 (3.29) | 6.20 (5.37) | 1.96 (4.83) | 3.38 | 0.87 |
| Total | 8 | 1780832 | 100 (12.12) | 100 (11.91) | 100 (11.71) | 2.35 | 1.64 |

^a RFEMS: Each RFEMS data takes 1 s. to collect. ^b Data collected using the observation method are used as the basis for comparison. ^c SD (The standard deviation).

**Fig. 4** Results of the time activity pattern showing the time for the eight workers staying in each micro-environmental zone.**Fig. 5** The linear plot of TAP activities collected using the questionnaire (a) and the RFEMS (b) methods vs. the results obtained with the observation method as the basis for comparison with numbers indicating the worker's ID No.

on noise exposure doses using the SND method and the standard PND methods. The noise exposure dose is expressed by time weight average (TWA) in dBA; the numbers represent the ID number of the eight workers involved in the study. The dashed line shows the 95% confidence intervals. In Fig. 6(a), the

correlation coefficient between the results obtained using the SND and the PND method is 0.915 with all data points in the 95% confidence intervals. This indicates high correlation between the results obtained using these two methods. Fig. 6(b) shows the errors of using the SND and the PND methods to measure the

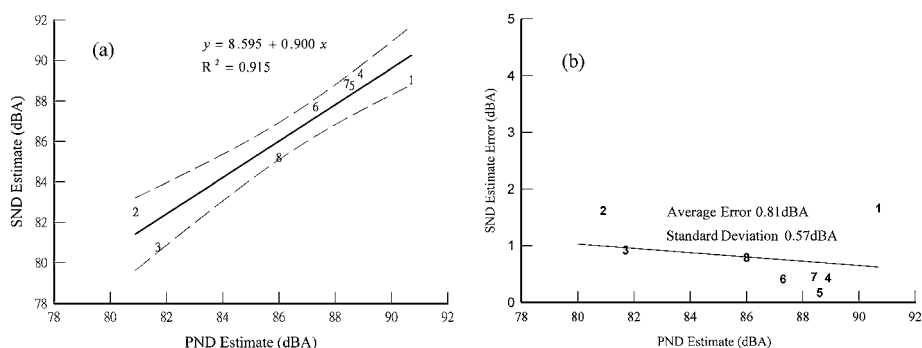


Fig. 6 Comparison of the SND and the PND results: (a) Linear regression, and (b) Errors. * Numeral: worker's ID number ** Dashed line: 95% confidence intervals.

noise exposure doses for the eight workers. The average error is 0.81 dBA between the SND and the PND methods with 0.57 dBA standard deviation of error. All TWA values are less than the allowable instrument reading errors (TES-1350A) of 2 dBA.

2. Real-time electronic recording indirect noise dosimetry (REIND). REIND is the indirect noise dose calculated based on the instantaneous sound pressure level and the time activity recorded by using RFEMS. Fig. 7(a) and Fig. 7(b) show respectively the linear regression of the results obtained using the REIND and the PND methods. The correlation coefficient for the eight workers being 0.779. Fig. 7(b) reveals that the average error expressed in TWA is 1.57 dBA and that the standard

deviation is 0.94 dBA. These results show that the REIND error of 1.57 dBA is slightly greater than the SND error of 0.81 dBA. The discrepancies may be caused by the difference between the environment noise and personal noise but they are within the allowable instrumental error of 2 dBA.

3. Equivalent electronic recording indirect noise dosimetry (EEIND). EEIND is a method for indirectly calculating the noise exposure dose based on the regional average Leq and the time activity recorded by using RFEMS. Fig. 8(a) show the linear regression analyses of the correlation between the results using the EEIND and the standard PND methods, and Fig. 8 (b) shows the measurement error. The results shown in Fig. 8(a)

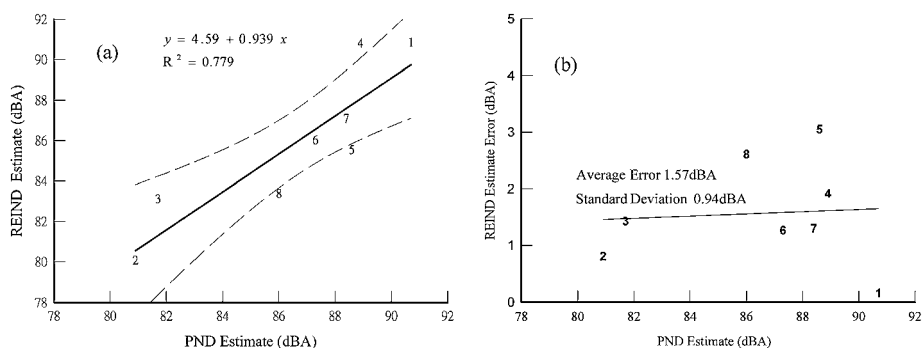


Fig. 7 Comparison of the REIND and the PND results: (a) Linear regression, and (b) Errors. * Numeral: worker's ID number ** Dashed line: 95% confidence intervals.

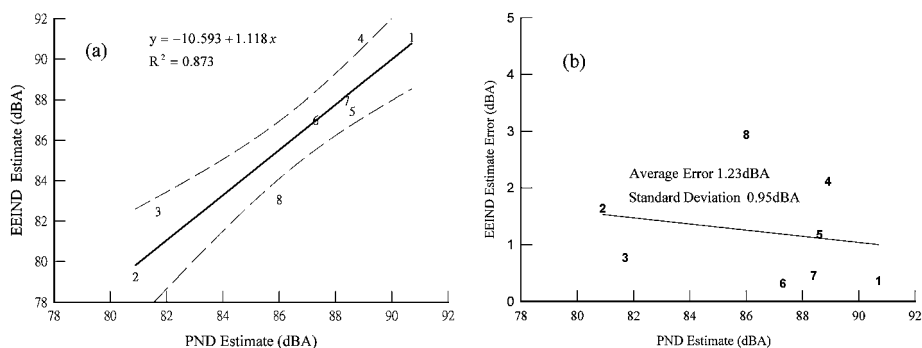


Fig. 8 Comparison of the EEIND and the PND results: (a) Linear regression, and (b) Errors. * Numeral: worker's ID number ** Dashed line: 95% confidence intervals.

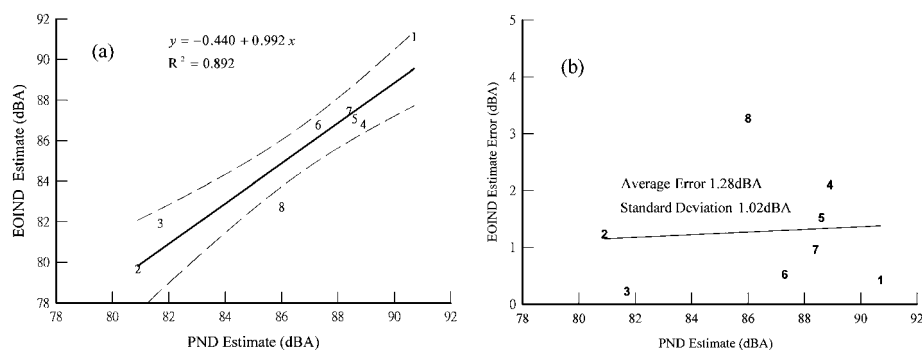


Fig. 9 Comparison of the EOIND and the PND results: (a) Linear regression, and (b) Errors. * Numeral: worker's ID number ** Dashed line: 95% confidence intervals.

indicate the correlation coefficient of 0.873 between REIND and PND results for the eight workers tested with TWA of 1.23 and standard deviation of 0.95 dBA. The results reveal that EEIND has a greater measurement error of 0.81 dBA than SND but the average error of 1.23 dBA is still below the allowable instrumental error level.

4. Equivalent observation recording indirect noise dosimetry (EOIND). EOIND is an indirect noise dose calculated using Leq and the time activity observed. The observation method is the standard method for verifying the time activity recorded using the RFEMS method. Hence, EOIND can be used as the standard for indirectly monitoring the noise dose level. The linear relationship between the results obtained using the EOIND and the PND methods are shown in Fig. 9(a) and Fig. 9(b), respectively. The correlation coefficient between the measured noise doses for the eight workers is 0.892 with 1.28 dBA TWA average error and 1.02 dBA standard deviation. Hence, EOIND has a greater monitoring error than SND but the difference is not significant.

5. Equivalent questionnaire recording indirect noise dosimetry (EQIND). EQIND is calculated from Leq and the time activity obtained from questionnaire. The questionnaire is easy to implement and thus is often accepted for recording time activity. Fig. 10(a) and Fig. 10(b) show respectively the correlation and error for analyzing the noise results obtained using the EQIND and the standard PND methods. For the eight workers, the correlation coefficient between EQIND and PND results is

0.663; the TWA measurement average error is 1.75 dBA with a standard deviation of 1.59 dBA. Hence, the correlation coefficient between EQIND and PND is the lowest and the error is the greatest among all noise calculation methods.

6. Results of verifying the noise exposure doses. The calculated noise exposure doses are summarized in Table 5. When PND is used as the standard method for monitoring the noise exposure dose, the RFEMS-enhanced inexpensive noise meter has the same SND result as with the more expensive noise dosimeter. The results have the maximum correlation coefficient ($R^2 = 0.915$) and the smallest error (0.81 dBA) with the standard method results. The EQIND obtained using the equivalent energy sound level (Leq), and the questionnaire methods have the worst correlation coefficient ($R^2 = 0.663$) and the highest error (1.75 dBA) among all monitoring methods. Additionally, the EEIND obtained using the equivalent energy sound level (Leq) method and the RFEMS method has a correlation coefficient of 0.873 (R^2) and monitoring error of 1.23 dBA, which are not much different from the R^2 value of 0.892 and error of 1.28 dBA for EOIND obtained using the Leq and the observation methods. These results indicate that for the microenvironment with stable noise, an accurate monitoring of the worker TAP will lead to accurate estimation of worker's noise exposure dose. Additionally, the results based on the RFEMS electronic observation have the same accuracy as those based on the observation method. Using the RFEMS method will greatly increase the number of observations with savings of manpower,

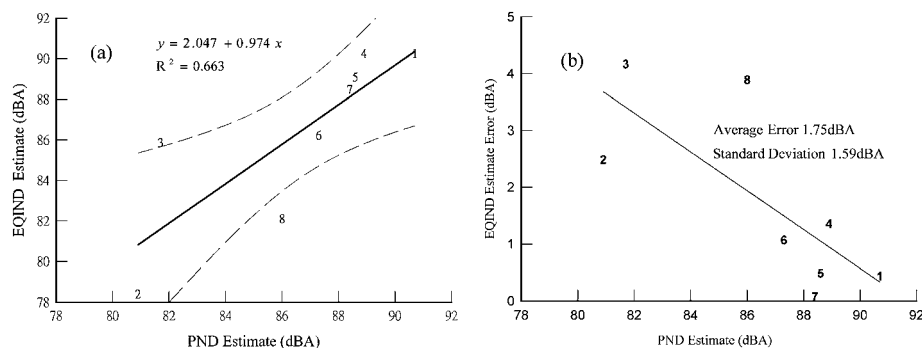


Fig. 10 Comparison of the EQIND and the PND result: (a) Linear regression, and (b) Errors. * Numeral: worker's ID number ** Dashed line: 95% confidence intervals.

Table 5 Comparison of the results obtained using the six different monitoring methods

| Category | Number of Workers | TWA (dBA) | Correlation Coefficient | TWA Errors (dBA) | SD ^a (dBA) |
|----------|-------------------|-----------|-------------------------|------------------|-----------------------|
| PND | 8 | 86.56 | 1 | 0 | 0 |
| SND | 8 | 86.53 | 0.915 | 0.81 | 0.57 |
| REIND | 8 | 85.87 | 0.779 | 1.57 | 0.94 |
| EEIND | 8 | 86.15 | 0.873 | 1.23 | 0.95 |
| EOIND | 8 | 85.44 | 0.892 | 1.28 | 1.02 |
| EQIND | 8 | 86.34 | 0.663 | 1.75 | 1.59 |

^a SD (The standard deviation).

and cost for conducting a long-term monitoring of noise exposure and evaluation of noise exposure.

Conclusion

The task-based RFEMS method is used to evaluate noise exposure in this research to accurately monitor the information on workers' exposure to noise. Combined with instant measurement of regional and personal noise levels using an inexpensive sound level meter, the proposed method will reveal noise exposure doses that are not much different from those acquired using the more expensive personal noise exposure dose. Minor errors may be caused by the physical deterioration of noise due to differences between the location of the worker and space location. However, as the exposure evaluation is concerned, using the proposed system to collect instant worker's time activity and regional noise level will obtain the results with the same accuracy as those obtained using the standard method. Additionally the RFEMS method will allow the researcher to cover more worker exposure information, explain the cause of noise exposure, make improvement recommendations and conduct long-term tracking of noise exposure. Its application will also reduce the equipment cost, and relieve the limitations of manpower needed for conducting further evaluation of noise exposure. Using the method recommended will assist in strengthening the research ability to study and analyze worker's operational mode, and the management of noise pollution.

Acknowledgements

The authors would like to thank the Institute of Occupational Safety and Health (IOSH), Council of Labor Affairs, Taiwan, ROC, for supporting this study.

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