ORIGINAl ARTICLE

Development of A New Exposure Monitoring System Considering Pulmonary Ventilation (DEM 1)

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Abstract

Exposure evaluation is an essential facet in the assessment of the risks of exposure to toxic materials in the workplace. Presently, samples from the breathing atmosphere are measured in order to determine the level of individual exposure to toxic substances. This method, however, does not take into account the level of physical exertion during exposure. Physical activity is known to increase pulmonary ventilation by up to 10 times that of the level at rest. Thus, measurement of pulmonary ventilation, as well as the concentration of a toxic material in the air would provide valuable data in evaluating exposure. We have developed a device that measures and records the concentration of a toxic material in the air and pulmonary ventilation as predicted by heart rate both simultaneously and continuously. In this system, real time pulmonary ventilation is predicted from heart rate by using a regression equation that was obtained from the results of our study. The percentage error of predicted pulmonary ventilation at each heart rate is within 30%. The present study assessed the feasibility of the use of heart rate as the predictor of pulmonary ventilation. Our new exposure monitoring system is the first practical device that monitors the level of exposure dependent upon pulmonary ventilation and will be useful in the revaluation of threshold limit values (TLV's) and in working management.

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A New Personal Exposure Monitoring System

Key words: toxic substance, risk assessment, exposure assessment, IC card, heart rate

Introduction

Exposure evaluation is an essential facet in the assessment of the risks of exposure to toxic materials in the workplace. The most useful parameter in determining the effect of a substance on an individual is measurement of its concentration in the target organ, but this can be a difficult and arduous process. Therefore, for substances incorporated through the airway, the most common procedure is to determine the individual exposure in terms of the concentration and length of exposure to the substance in the breathing zone. There are, however, several variables which may cause the exposure concentration and the concentration in the target organ to differ. One of these is physical activity. Physical activity is known to increase pulmonary ventilation by up to 10 times the level at rest. Increased pulmonary ventilation leads to an increase in the uptake of a toxic material and to the amount deposited. Moreover, increased pulmonary ventilation also affects circulation as well as the metabolic rate. For these reasons, measurement of pulmonary ventilation in addition to measurement of the concentration of a toxic material and would provide useful information in the evaluation of exposure.

A dust sampler reported by Kucharski, in which the sampling flow varies according to pulmonary ventilation, has been the only device developed to date that has the ability to measure exposure dependent upon pulmonary ventilation. Actual use of this apparatus in the workplace, however, has not been reported. We have developed a device that measures and records the concentration of a toxic material and pulmonary ventilation as predicted by heart rate both simultaneously and continuously. The purpose of this paper is to introduce this system, the principles behind its development, and the theory supporting the resultant regression equations that were used.

Materials and Methods

Description of the system

Figure 1 shows a schematic diagram of the system used in the present study. The system consists of five parts: various sensors, a data-logger, an IC card, a data reader, a computer system and its software. Below are descriptions of each part of this system.

(1) Sensors: The system includes sensors for dust, solvents, heart rate, ambient temperature, body temperature and level of physical activity.

Dust sensor: This is a mini Real Time Aerosol Monitor (RAM), a small-sized
dust measuring device manufactured by the MIE Corp., USA, which measures mass concentrations by a light scattering detector.

**Solvent sensor:** This is an organic solvent sensor that we recently developed. It is a continuous measuring device based upon semiconductors. The sensor is composed of grooved 2×3 mm silicone chips with bridges constructed of thin platinum membrane heaters and SnO₂-sensing membranes. The sensor works on the following principle: adhesion of an organic solvent to the sensing membrane causes changes in its resistance, which can be measured as changes in voltage. For most organic solvents, concentration shows close correlation with resistance.

**Heart rate sensor:** Vitrode G-80 electrodes manufactured by (Nihon Kohden Corp.) are used. The mean R-R interval in a 30-second ECG recording is used as the heart rate.

**Physical activity rate meter (accelerometer):** An accelerometer (MT-3; Nihon Kohden Corp.) that detects changes in intensity or form of work is used to measure the physical activity rate.

**Thermo sensor** (for body temperature and ambient temperature): Ambient temperature sensors provides additional ambient data on the workers. Body temperature sensors detects changes in the body's thermal response to the environment.

(2) **Data-logger:** A data-logger is used to digitize the analog data from the sensors and to record the data on the IC card. The data logger was attached to each worker by a special belt. The specifications are shown in Table 1. The measuring time, ID number, measuring channel and measuring interval could be input from a keyboard on the upper panel. Abnormal inputs and low battery levels during measurement are
indicated by an audible alarm. This unit also has a "pause" function and a "marker" function, the latter function allowing for marking of significant changes in work activity by the worker himself (Fig. 2).

(3) IC-card: The digitized data is recorded on the IC card. The digital data is then read into the computer by the card reader and processed. The IC card has a memory capacity of 256K bytes, sufficient for data collected over 8 hours, if all channels were in constant use at 30 second intervals. Continuous use of the main unit, the data logger, is possible by changing the IC card when necessary.

(4) Readout unit: Data recorded on the IC card is recorded onto a floppy disk by the readout unit connected to the computer. This readout unit performed instantaneous readouts.

(5) Personal computer: NEC's PC9801 (over 384 KB of main memory). Additional hardware included dual floppy disk drives, color video monitor, and color printer.

(6) Software: The software consists of N88 BASIC. This is used to process the data recorded on the IC card. It was programmed to predict pulmonary ventilation from heart rate. When the individual data is input, pulmonary ventilation is calculated at each point of measurement. The software also includes three graphic functions that plots serial changes for each value. The time axis is arbitrary for these graphs (Fig. 3).

**Prediction of pulmonary ventilation from heart rate**

It is possible to directly measure pulmonary ventilation by using a heat ray flowmeter with mask, but this procedure burdens the worker and may not reflect the true intensity of work. Another method for measuring pulmonary ventilation is prediction from thoracic movement, but this method is not appropriate for moving subjects.
Therefore, we employed a procedure that predicts pulmonary ventilation during work on the basis of heart rate. A number of reports have shown that the heart rate is highly correlated with oxygen consumption.\textsuperscript{14-16} In particular, it has been reported that the correlation is high for aerobic respiration during relatively high activity.\textsuperscript{17} However, there have not been any studies conducted on the prediction of changes in pulmonary ventilation from changes in heart rate. In developing the present system, we first evaluated whether or not prediction of pulmonary ventilation from the heart rate is possible in the workplace (Study 1). We then carried out an experiment to produce a method of prediction which allowed for incorporation of this method of calculation...
Study 1: The subjects were 12 healthy adult males (Age: mean 23.8 y/o, range 21–32. Height: 171.3 cm, 162–184. Weight: 69.4 kg, 52–86). Submaximal heart rate and pulmonary ventilation were measured by using three types of exercise: running on a treadmill, exercising on an ergometer, and lifting a heavy object (5 kg weight). Exercise on the treadmill and ergometer was gradually increased under controlled conditions to achieve stability at each heart rate level. In the lifting of a weight, the subjects repeated a single motion, that of lifting a heavy object from the floor to their waist and then setting it down again. Heart rate and pulmonary ventilation were measured by using a microcomputer-based respiratory analyzer (Aerobic Processor; NEC-SANEI, Japan).

Study 2: The subjects were 34 healthy male adults (Age: mean 30.4 y/o, range 21–52. Height: 168.3 cm, 162–184. Weight: 63.4 kg, 52–86). Heart rate and pulmonary ventilation were measured during gradually increased exercises similar to those in Study 1 on the treadmill. A SAS statistics package was used for preliminary statistical processing prior to predicting pulmonary ventilation from heart rate.
Results and Discussion

Study 1: The Table 2 shows the relationships between heart rate and pulmonary ventilation during exercise on the ergometer for each of the 12 subjects. Correlation of the individual coefficients between heart rate and pulmonary ventilation was high, but the inter-individual regressions showed considerable differences, suggesting that correction for individual characteristics would yield better prediction results.

The relationship between pulmonary ventilation and heart rate during various exercises is shown in Fig. 4. It has been reported that during submaximal exercise no significant difference is observed between bicycle ergometry and treadmill running on the relationship of heart rate and pulmonary ventilation at any level of oxygen consumption.\textsuperscript{18,19} There have been other reports, though, in which slightly higher values for heart rate and pulmonary ventilation during bicycle exercise have been obtained.\textsuperscript{20,21} Similarly, at a submaximal work level, no important differences were found between the effects of leg exercise and of arm exercise in either a sitting or standing body position on heart rate and pulmonary ventilation.\textsuperscript{22} Our results are in agreement with these reports. The differences in pulmonary ventilation due to exercise at each heart rate level observed in our experiment are 10\% to 20\% in most cases. These results indicated that prediction of pulmonary ventilation from heart rate is possible when individual characteristics are taken into account. Also from the above results, exercise at the workplace was represented by exercise on a treadmill in our study.

Study 2: Correction for individual characteristics posed a problem. We regarded age and vital capacity as factors influencing pulmonary ventilation, and sports history

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Regression equation*</th>
<th>n</th>
<th>R</th>
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<tr>
<td></td>
<td>Y = 0.0286 X - 0.0755</td>
<td>8</td>
<td>0.974</td>
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<td>Y = 0.0284 X - 0.2278</td>
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\*X: heart rate, Y: log $\dot{V}_E$
Fig. 4 Relationships between pulmonary ventilation and heart rate in various exercise.

$\Delta$HR: observed HR—resting HR, $\dot{V}_E$: pulmonary ventilation

and age as those affecting heart rate. Sports history, which cannot be evaluated quantitatively, was substituted with resting heart rate. Vital capacity is also considered to be difficult to measure at the workplace and was calculated from height, body weight, age, and resting heart rate. The resultant regression equation is shown below:

$$\log \dot{V}_E = (9.38 \times X_1 + 4.22 \times X_2 + 1.19 \times X_3 + 2.22 \times X_4 + X_5) \times 10^{-3} - 0.0439$$

$\dot{V}_E$: pulmonary ventilation (l/min)  
$X_1$: $\Delta$HR (beats/min)  
$X_2$: age (year-old)  
$X_3$: resting HR  
$X_4$: height (cm)  
$X_5$: weight (kg)
Figure 5 shows the differences between the predicted pulmonary ventilation obtained by this equation and the observed pulmonary ventilation. The percentage of error at each heart rate level is less than 30%.

In the actual workplace, exercise is varied, and various other factors—such as bated breath and emotional stress—affect pulmonary ventilation and heart rate. Therefore, accurate prediction of pulmonary ventilation from heart rate is difficult. The purpose of our system is, however, to determine exposure based upon changes in physical exertion and thus fluctuations in these values due to the type of exercise were considered permissible. When the effects of the various individual characteristics are taken into consideration for the calculation, a high correlation between heart rate and ventila-
tion is obtained. The regression calculated from this study was thus incorporated into the software of the present system.

In the case of exposure to solvents, poor correlation between the exposure concentration and the biological monitoring value is often observed. This is largely due to the fact that concentration in the atmosphere does not always represent the amount of intake. There is a consensus\textsuperscript{5-6,9} that a more realistic exposure value can be obtained by taking pulmonary ventilation into consideration. To date, however, a practical device that gave information on both pulmonary ventilation as well as exposure concentration did not exist. Our new exposure monitoring system (DEM 1) is the first practical device that can monitor the level of exposure dependent upon pulmonary ventilation. It is our opinion that it will be useful in the revaluation of TLV values and working management.

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