DEVELOPMENT OF A NEW PERSONAL EXPOSURE MEASUREMENT SYSTEM CONSIDERING PULMONARY VENTILATION

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ABSTRACT

The pulmonary ventilation is a critical factor for determining the intake of airborne pollutants. However, the present widely used monitoring for the evaluation of occupational exposures tends to ignore it. We have developed a monitor on experimental basis (HMR-3) with the function of measuring the real-time pulmonary ventilation in order to evaluate the actual exposure level, and presented it at ICOH, Sydney in 1987. On the findings obtained by HMR-3, we developed an improved device (DEM-1) which is sufficient for practical use in size and function.

DEM-1 system consists of four components. (1) Sensors for heart rate, for ambient dust concentration (mini-RAM), for body and environmental temperature, and for acceleration, (2) the data-logger which collects and inputs the data into IC-card, (3) the IC-card reader for the personal computer, (4) soft-wares for data processing. In this system, real-time pulmonary ventilation volume is predicted from average heart rate every 30 seconds using a conversion formula which includes the rate of change in heart rate, age, height and weight for each subject as explanatory variables.

Furthermore, DEM-1 has the following advantages. (1) By replacing the IC-card, the data-logger can be used continuously. (2) Capable of displaying the level of movement by acceleration sensor simultaneously, it is helpful for separately determining the degree of occupational hazards in each working unit.

INTRODUCTION

Exposure evaluation is indispensable for assessing the risk of airborne dusts in the workplace. Presently, when determining the level of individual exposure to airborne dusts, measurements are made by taking a sample from breathing zone. Those methods, however, do not take into account the level of physical exertion during exposure. Physical activity is known to increase pulmonary ventilation by about 10 times the level at rest.[1,2] Increased pulmonary ventilation causes an increment in the uptake of respirable dusts and affects the amount deposited.[3]

Thus, measurement of pulmonary ventilation, as well as the air concentration of airborne dusts, could seem to provide highly useful data in evaluating exposure. We have developed an instrument on experimental basis (HMR-3) for measuring exposure to air pollutants that continuously measures the concentration of air pollutants and the ventilation volume simultaneously, and presented it at ICOH, Sydney in 1987.[4] In this system, real-time pulmonary ventilation volume is predicted from average heart rate every 30 seconds using a conversion formula which includes the rate of change in heart rate, age, height and weight for each subject as explanatory variables. On the findings obtained by HMR-3, we developed an improved device (DEM-1) which is sufficient for practical use in size and function.

METHODS

Description of the System

Figure 1 shows the system outlines of the device (DEM-1). DEM-1 system consists of four components. 1) Sensors for heart rate, for ambient dust concentration, for body and ambient temperature, and for acceleration, 2) the data-logger which collects and inputs the data into IC-cards, 3) the IC-card reader for the personal computer, 4) soft-wares for data processing.

Dust sensor: This is a mini RAM, a small-sized dust measuring device manufactured by MIE, U.S.A., which measures mass concentrations by a light scatter detector.

Heart rate sensor: Electrodes Vitrode G-80 manufactured by Nihon Kohden Co. is used. The mean of the R-R intervals in a 30-second ECG recording represents the heart rate.

Accelerometer: An accelerometer (MT-3; Nihon Kohden Co.) that picks up changes in the intensity or the form of work

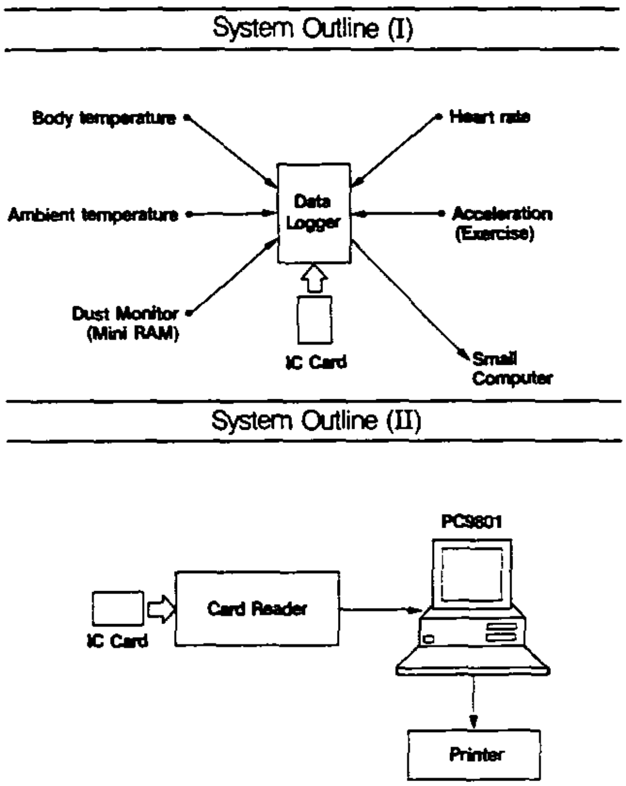


Figure 1. Essential components of DEM-1 and flow chart of data processing.

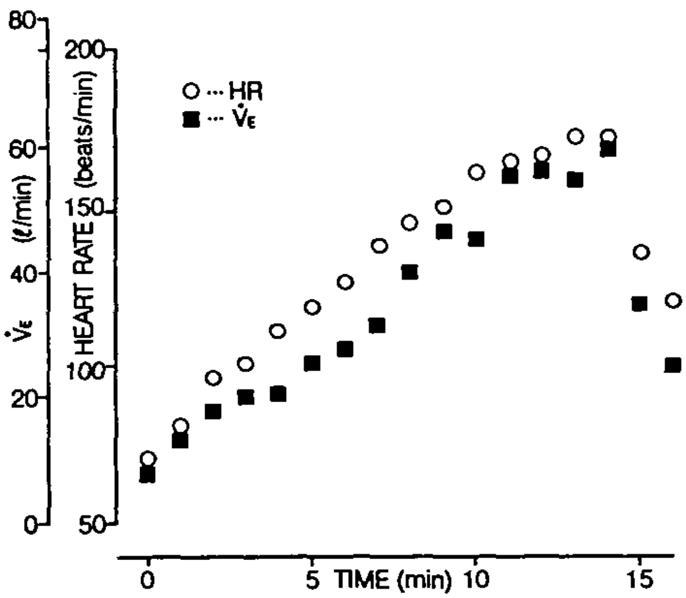


Figure 2. Typical HR response and $\dot{V}_E$ during graded exercise test using a treadmill.

is used as a sensor for physical activity.

Thermo sensor: This body and ambient temperature sensor provides additional ambient data on workers.

Data-logger: Analogue-data output from each sensor are A/D converted by the data-logger and recorded on the IC-card. The data-logger is attached to each worker by an exclusive belt. The measuring time, ID number, measuring channels are input by the keybord on the surface of data-logger.

IC-card: Digitalized data are recorded on the IC-card, read into the computer by the card reader and processed. Since the IC-card has a memory capacity of 128 K bit and can store data collected during 10 hours, data in all channels are recorded at intervals of 30 seconds.

Card reader: Data recorded on the IC card are recorded into a floppy disk by the card reader connected to the computer.

Personal computer: The hardware (PC-9801, NEC, Japan) includes dual floppy disk drives, color video monitor and color printer as options.

Laboratory Testing of DEM-1 System

For determining the regression equation between the ventilation volume and the heart rate, heart rate and pulmonary ventilation were measured up to submaximal level using treadmill. Heart rate and pulmonary ventilation were measured by using a microcomputer-based respiratory analyzer (Aerobic Processor: NEC-Sanei, Japan).

The subjects were 34 healthy male adults, aged 17 to 62 years. Exercises on the treadmill were gradually increased under controlled conditions to achieve stability at each heart rate level, such as +20%HR, +40%HR, +60%HR and so on. Figure 2 shows a typical pattern of heart rate change and ventilation volume during graded exercise test using treadmill and these findings indicate the correlation between the two values. Figure 3 shows the difference of heart rate-ventilation volume relationships among the subjects.

According to these findings, heart rate at resting condition (base HR), difference between heart rate in each graded exercise and base HR (ΔHR), ΔHR/base HR, age, height, weight, BMI (body mass index) were selected as initial explanatory variables for multiple regression equation to predict the ventilation volume.

Statistical processing in preparing to predict pulmonary ventilation from heart rate was performed using the multiple regression analysis program in SAS.

RESULTS AND DISCUSSION

Figure 4 shows the resultant regression equation for predicting the ventilation volume from heart rate. Base HR, ΔHR, height, weight and age remained as significant explanatory variables. Differences between the predicted pulmonary ventilation volume obtained by this equation and observed pulmonary ventilation are shown in Figure 5. The percentage of error at each heart rate level was less than 20%, for 25

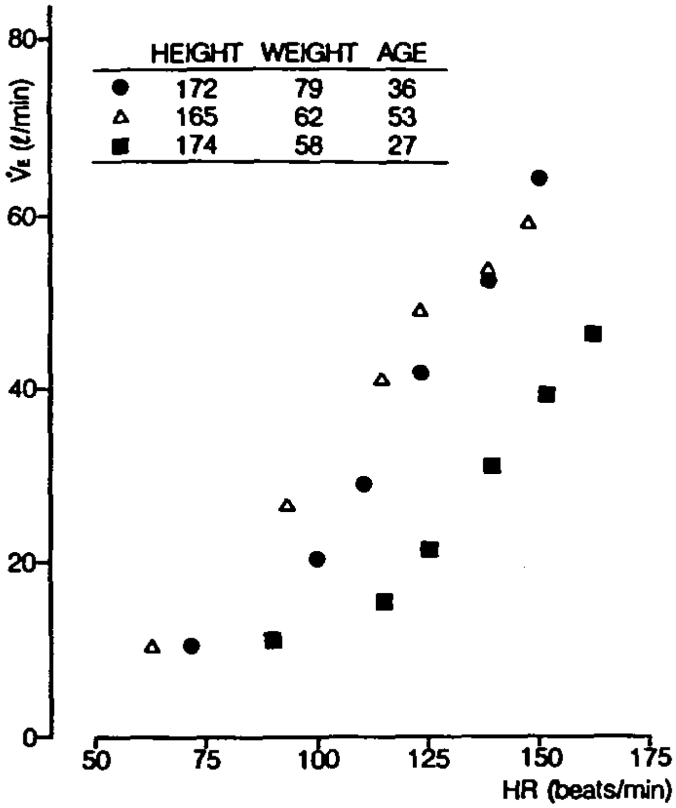


Figure 3. Difference of HR-$\dot{V}_E$ relationships among subjects.

subjects, the differences were less than 10% in each exercise level.

Figure 6 shows a sample of graphic of 1 hour monitoring. The upper photograph abbreviations mean the following, VE: ventilation volume predicted from heart rate (liter/min), BT, ET: body and ambient temperature (centidegree), DC: dust concentration (mg/cubic m), MI: indices of movement. In the lower photograph, Intake means the predicted exposure (mg) that dust concentration was multiplied by predicted ventilation volume.

To assess personal exposure better, measurement of ventilation volume is indispensable.[5] There are some methods for measuring ventilation volume as following. The first method is direct measurement of the exhalation or inhalation volume and there are several techniques for performing this. However, the subject must wear a mask or mouthpiece. This is uncomfortable, therefore the subject is under an additional amount of determined physical stress, including the increase of respiratory resistance due to wearing the equipment. Because of this, actual ventilation volume measurement may not be possible due to increase. In one indirect measurement method, ventilation volume is calculated from movement of the thorax. With this method, it is easy to see the strong correlation between movement of the chest and the ventilation volume in a state of physical rest.[6] However, accurate measurement during physical exertion is difficult.

Kucharski confirmed high correlation between heart rate and ventilation volume, and developed a personal dust sampler in which sampling air flow rate varies depending on heart rate. This sampler has been the sole device available for measuring

$$\mathrm{Log}\ \dot{V}_E = 0.00938 \times X_1 + 0.00422 \times X_2 + 0.00119 \times X_3 + 0.00222 \times X_4 + 0.00335 \times X_5 - 0.0439$$

X_1: ΔHR
X_2: HEIGHT
X_3: WEIGHT
X_4: AGE
X_5: base HR

Figure 4. Regression equation calculated from the data of 34 healthy male volunteers.

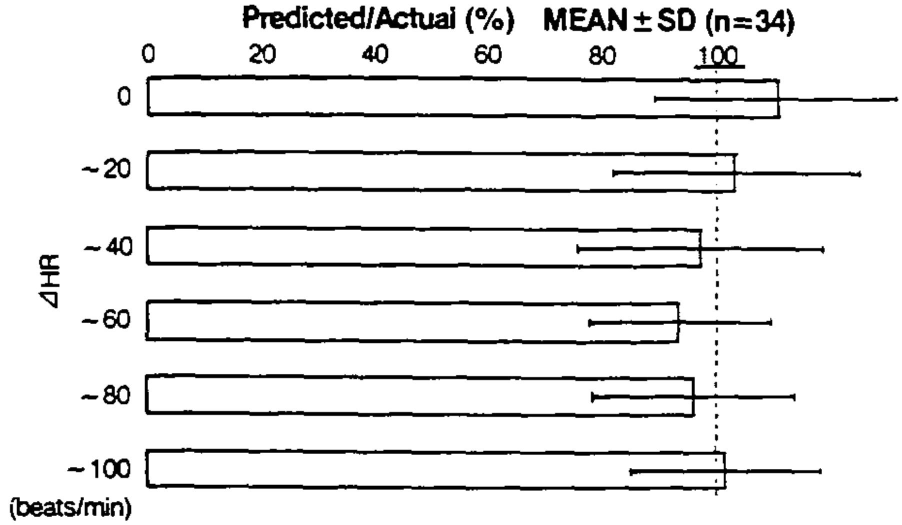


Figure 5. Difference between predicted values and actual values at each heart rate level.

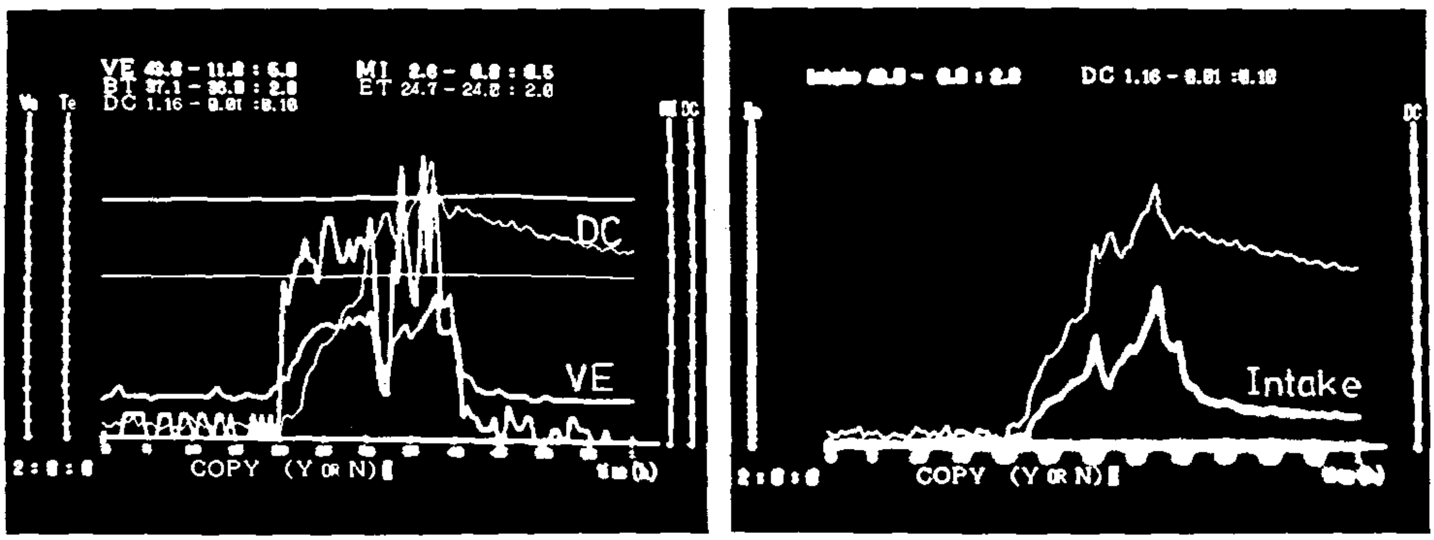


Figure 6. A sample of graphic output on VDU.

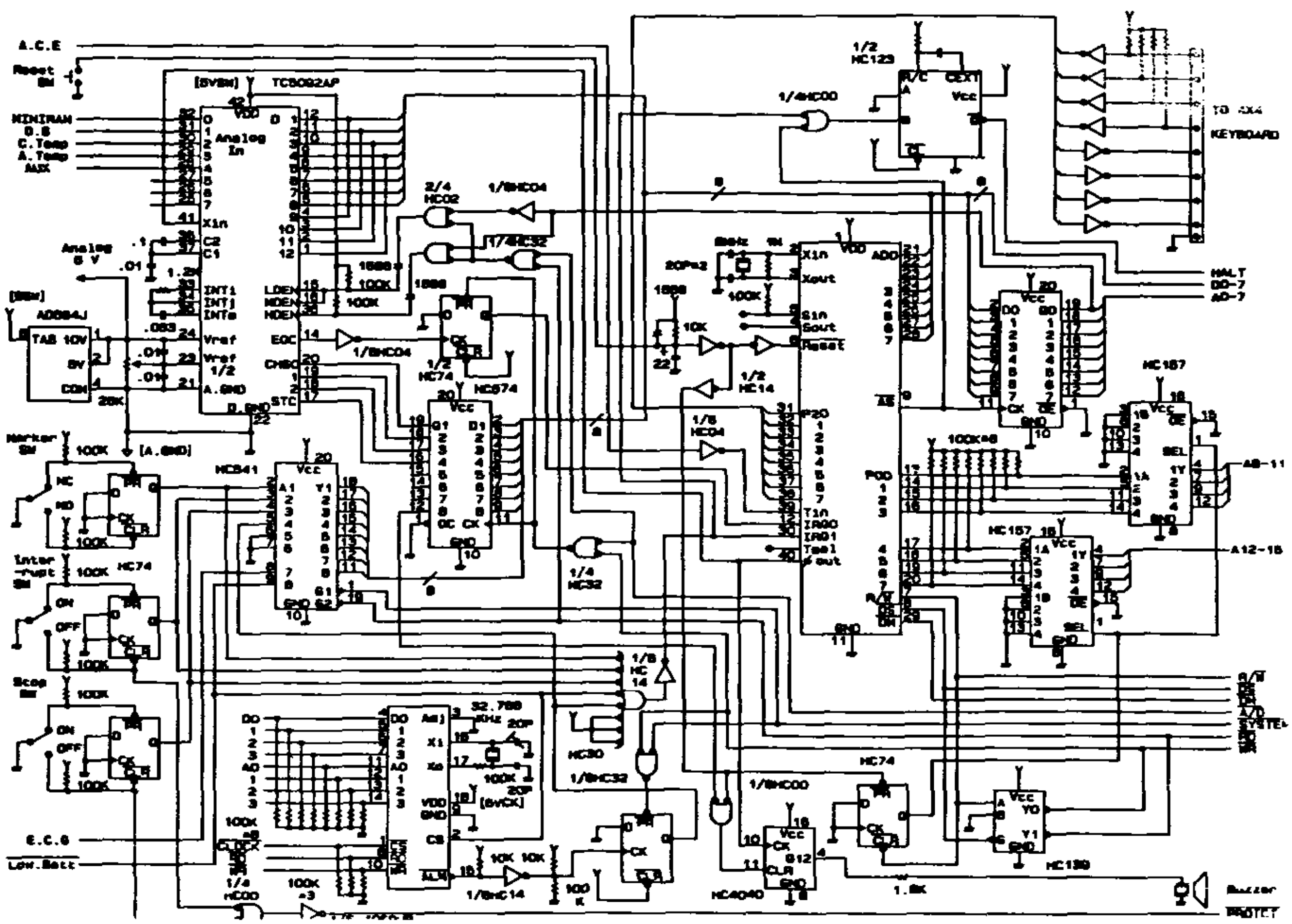
exposure in association with pulmonary ventilation.[7] We also observed the high correlation between the heart rate and the ventilation volume and made a prediction equation. Advantages of our system compared with that of Kucharski are to evaluate the real time dust concentration and ventilation which are useful for assessing the various work conditions.

At actual workplaces, exercise is varied, and there are various factors affecting pulmonary ventilation and heart rate, such as breath-holding and mental stress. However, differences in values due to differences in type of exercise were permissible in view of purpose of our system.[4]

The problems, such as deposition rate of particles depending on their size distribution which is an important factor for assessing actual exposure, and development of more unrestrictive methods to measure heart rate, still remain unsolved.

CONCLUSION

1. We developed a system that continuously measures airborne dust concentration and heart rate to predict ventilation volume, simultaneously.
2. Ventilation volume can be calculated with the heart rate. The difference between the predicted value and the actual recorded value is negligible for practical use.
3. With this instrument, the actual intake volume could be more accurately evaluated compared with the methods heretofore.
4. Electrodes of heart rate sensor is slightly restrictive for workers. Improvement is necessary in this point.



REFERENCES

1. Bjorn, E., Astrand, P.O., et al: Effect of training on circulatory response to exercise. *J. Appl. Physiol.* 24:518-528 (1968).
2. Consolazio, C.F., Nelson, R.A., et al: Body weight, heart rate, and ventilatory volume relationships to oxygen uptakes. *Am. J. Clin. Nutrition* 24:1180-1185 (1971).
3. McMahon, T.A., Brain, J.D., Lemott, S.: *Species differences in aerosol deposition, inhaled particles IV*, part 1, pp. 23-45, Pergamon Press, Oxford (1977).
4. Satoh, T., Higashi, T., Sakurai, H.: Development of a new device for personal exposure measurement considering ventilation volume. *XXII International Congress on Occupational Health*, Sydney, Australia (27 September–2 October, 1987).
5. Sharky, B.J.: Pulse rate and pulmonary ventilation as predictors of human energy cost. *Ergonomics* 9:223-227 (1966).
6. Hill, S.L., Blackburn, J.P., Williams, T.R.: Measurement of respiratory flow by inductance pneumography. *Medical & Biological Engineering & Computing*. 20:517-518 (1982).
7. Kucharski, R.: A personal dust sampler simulating variable human lung function. *Brit. J. Industr. Med.* 37:194-196 (1980).

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