Microcomputer-based respiratory function monitoring system using impedance pneumography

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Abstract—*Although information concerned with ventilatory dynamics is indispensable, especially with regard to the care of a critically ill patient, the data available is often very limited, because the currently used methods of ascertaining data are invasive and not tolerable for patients who are still conscious and neither intubated nor tracheotomised. From this viewpoint, a respiratory function monitoring system was developed, using a non-invasive ventilatory volume monitor based on the electrical impedance method as a key component. The system is composed of two ventilatory volume monitors connected to two patients and a central monitor. The central monitor acquires on-line data transmitted from ventilatory volume monitors and stores then in floppy-disc memory together with off-line data, such as blood gases, blood chemistry and urine volume. These data may be retrieved and displayed on a visual display unit in the form of tables, trend graphs or specially designed graphs. Hard copies can be made on demand. According to the accumulated results obtained from respiratory failure patients, it is now clear that the introduction of the system into medical practice would facilitate more accurate analysis of respiratory and circulatory pathophysiology for the type of patient mentioned. Furthermore, the physical responses to various respiratory and circulatory treatments can be obtained in more detail and the course of these patients' illness can be reviewed more systematically.*

Keywords—*Impedance pneumography, Microcomputer, Monitoring system, Respiratory function*

1 Introduction

WITH the progress in microcomputer technology and sensor technology, great strides have been made in the development of various patient monitoring equipments and systems. In particular the improvement in the quality of cardiovascular function monitoring, such as arrhythmia monitoring (SHAH *et al.*, 1977) and haemodynamic monitoring (BUCHBINDER *et al.*, 1976) is quite remarkable. In parallel with these trends, methods of monitoring the respiratory function of critically ill patients, on which patient life directly depends, are also being explored. However, the methods were mostly designed to monitor patients under artificial ventilation (OSBORN, 1977; WILSON, 1976), and proper monitoring systems were not available for patients who were neither intubated nor tracheotomised. The reason for this lay in the difficulty in measuring ventilatory volume non-invasively, which is basic to respiratory function monitoring.

With these factors in mind, a ventilatory volume monitor was developed (ITOH *et al.*, 1981), which monitors ventilatory volume non-invasively, using the electrical impedance method, instead of a pneumotachograph (TURNEY *et al.*, 1973) or Wright respirometer (CRANE *et al.*, 1976). Then, an attempt was made to systematise respiratory function monitoring.

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This paper describes the present respiratory function monitoring system. First the hardware, software and operation are considered and then the results obtained from the system are detailed, quoting clinical application examples.

2 Respiratory function monitoring system

2.1 *System hardware configuration*

The system employs a non-invasive ventilatory volume monitor, using impedance pneumography as a key component. As shown in Fig. 1, it consists of two ventilatory volume monitors at the bedside and a microcomputer-controlled central monitor placed at the nurse station. Floppy disc memory, a graphic display, a hard-copy apparatus, a pen recorder and two keyboards are connected to the microcomputer in the central monitor. From the ventilatory volume monitor, on-line signals, such as respiratory waveform, respiratory rate, tidal volume, minute ventilation volume, e.c.g. and heart rate, are supplied. The central monitor collects these signals periodically and automatically and files them in the floppy disc memory.

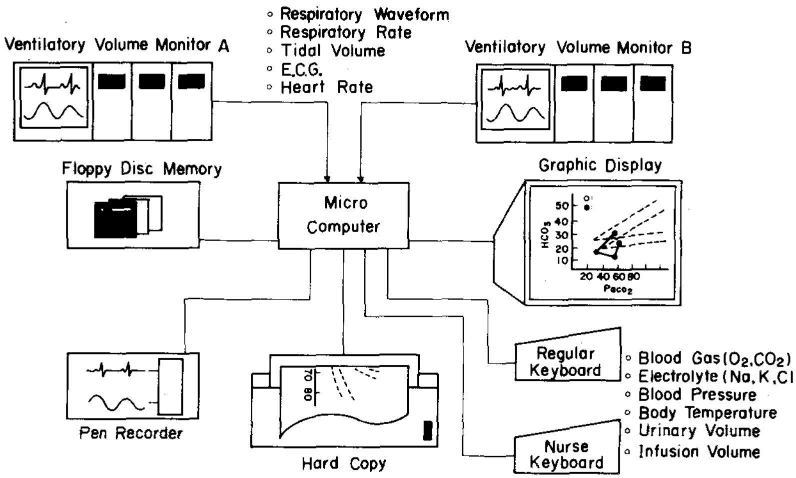


Fig. 1 *Respiratory function monitoring system blockdiagram*

The data filed in the floppy-disc memory can be displayed on a visual display unit in the form of tables, trend graphs or specified graphs combining several kinds of data, according to the instruction sent from the keyboards. The displayed image can be hard-copied on a thermal recorder when desired. Also, data filed in the floppy-disc memory can be hard-copied automatically and at any desired frequency, for example once a day, in graph format. The on-line signals sent from the ventilatory volume monitor can be recorded, together with the patient's name and time of recording. This recording is carried out under microcomputer control at a time interval specified by an operator.

The two keyboards, a nurse's keyboard and a regular keyboard, are used to operate the system and to input off-line data. The nurse's keyboard is a simplified one, specially designed to be used daily by nurses. The regular keyboard is able to fully utilise all the system functions, such as patient registration, data retrieval, data input and data display. Off-line data includes blood gas, blood chemistry, urine volume and infusion volume.

Table 1 shows the main specifications for the system.

2.2 *System software configuration*

In this system, real-time processing is required because on-line signals provided by the ventilatory volume monitor should be collected automatically and periodically, and filed in the floppy-disc memory. Furthermore, the system is able to execute several processes which are requested concurrently. For example, the system responds to an operator command, which is fed from a keyboard asynchronously, at a given time together with signal acquisition.

To deal with these requirements, system functions are divided into tasks. Each task is assigned a proper priority level and executed under the control of a real-

Table 1. Main system specifications

Data	
On-line	12 (tidal volume, respiratory rate, heart rate, ECG, respiratory waveform etc.)
Off-line	32 (blood gas, electrolyte, urinary volume, infusion volume, blood cell count etc.)
Data File	
Filing apparatus	three floppy disk drives for two patients' data and system program
Filing capacity	patient's data for four weeks/disk
Data Output	
Display format	trendgraph, table and other graphic display
Hard copy	thermal printer for graphic display pen recorder for biological data waveform
Data processing	micro-computer (TMP 9080AC, 40K byte RAM, 24K byte ROM) and arithmetic processor

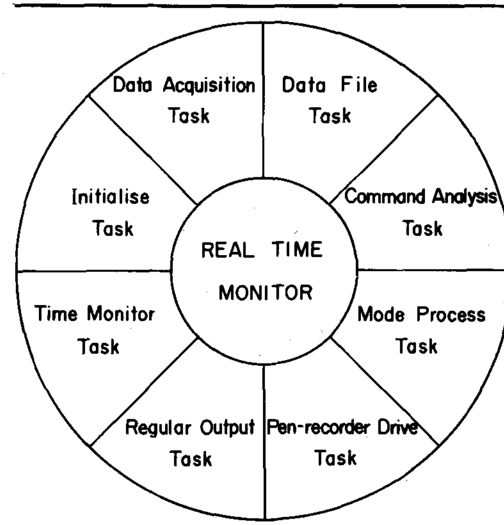


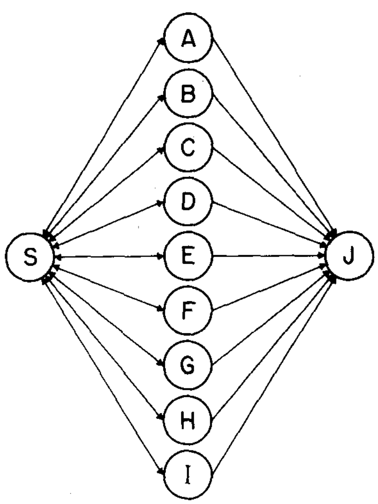
Fig. 2 *System software configuration*

time monitor prŏgram. The real-time monitor determines which task should be executed next and provides a means of controlling and exchanging data within the system, the software configuration is shown in Fig. 2. When a command requesting filed data display is sent from a keyboard, the command is first analysed by the command analysis task. Next, the data file task reads the proper data stored in the floppy disc memory. Finally, the mode process task makes a display image, using these data, and sends the data to the graphic display.

This system has many functions in special display formats. The program cannot be stored complete in the 64k byte memory space provided by an 8-bit microprocessor. Therefore, parts of programs, which are independent from each other, are overlaid in the memory map.

2.3 *System operation*

The system can be operated interactively according to the mode transition diagram shown in the upper part of Fig. 3. Letters S, A ~ I and J in Fig. 3 are assigned to every mode of the system function, as shown in Table 2. First, mode S is activated after the power is turned on and the function list provided is displayed on the graphic display. An operator can select the next mode by key operation shown in the lower part of Fig. 3. For example, mode D is used to display trend graphs, whose abscissa axis parameters are variable from one to four. The time span for the ordinate axis is prepared for between one hour and one week. Mode F is used to display specially designed graphs, such as the O_2–CO_2 diagram, acid-base balance diagram, respiratory profile and water balance diagram. Mode G is used to display graphs in combination with the O_2-CO_2 diagram, and the minute volume trend graph or blood gas table.



Current Mode	Next Mode	Operation
S	⇨ A~I	Push Key A~I
A~I	⇨ S	Push (CTRL) and Key S
A~I	⇨ J	Push (CTRL) and Key C

(S, A, B, C, D, E, F, G, H, I and J meanings are given in Table 2)

Fig. 3 *Mode transition diagram and key operation table*

3 Clinical results

Figs. 4 to 8 show results accumulated through an entire clinical course for a patient who was hospitalised in the Jichi Medical School. Data were acquired through monitoring by the system. The

Table 2. Modes and their functions in the system

MODE	FUNCTION
A	Input Patient Data
B	Input Offline Data
C	Display Table
D	Display Trendgraph
E	Display Waveform
F	Display Special Graph
G	Display Combination Graph
H	Input Comment
I	Drive Pen-recorder
J	Hard Copy
S	Display Function List

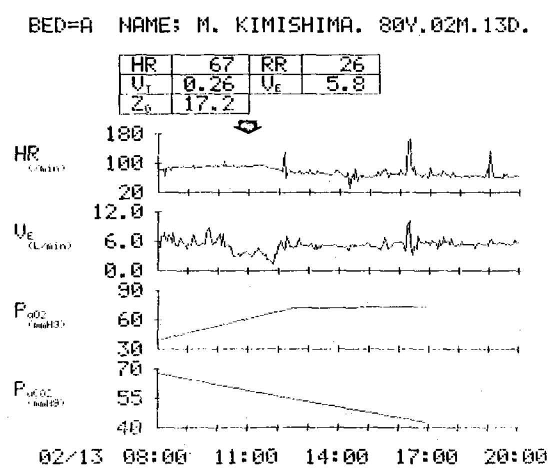


Fig. 4 *Effect of tracheotomy (carried out at the arrow) on the heart rate HR, minute ventilation volume $\dot{V}_E$, arterial oxygen and carbon dioxide partial pressures paO_2 and $paCO_2$, shown in trend graphs from 8 a.m. to 8 p.m.*

patient was in acute respiratory failure with right heart failure due to old pulmonary tuberculosis. At admission, the tensions for oxygen and carbon dioxide in arterial blood were 41 mmHg and 52 mmHg, respectively. Immediately, low flow rate oxygen therapy was carried out and diuretic medication was undertaken to reduce the load on the heart. However,

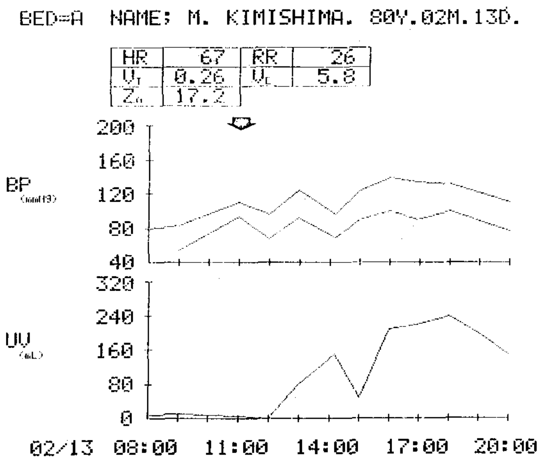


Fig. 5 *Effect of a tracheotomy on the blood pressure BP and urine volume per hour UV, shown in trend graphs for the same time interval as in Fig.* 4

the arterial oxygen tension did not improve, the arterial carbon dioxide tension increased and the urine volume was decreased.

From Fig. 4 and Fig. 5, data concerning the heart rate HR, minute ventilation volume $\dot{V}_E$, arterial oxygen and carbon dioxide partial pressure $pa\mathrm{O}_2$ and $pa\mathrm{CO}_2$, arterial blood pressure BP and urine volume UV were retrieved and are shown as trend graphs. These data were stored as on-line data and off-line data in the system, from 8 a.m. to 8 p.m. on 13th February. Before tracheotomy, the blood pressure was less than 100 mmHg and unstable, and the urine volume was almost nill, in spite of the treatment, as indicated in Fig. 5. The trend graphs in Figs. 4 and 5 clearly show that a tracheotomy, carried out at 11 a.m. (shown by black arrows), produced reductions in the heart rate and arterial carbon dioxide tension as well as increases in the arterial oxygen tension, arterial blood pressure and urine volume, without an event increasing in minute ventilation volume.

Fig. 6 shows an O_2–CO_2 diagram (SYKES *et al.*, 1971) for blood gas data, fed in from a keyboard and filed in a floppy disc memory. The X and Y axes imply oxygen and carbon dioxide tension in arterial blood $pa\mathrm{O}_2$ and $pa\mathrm{CO}_2$. The dotted oblique line is derived from the alveolar air equation on the assumption that the partial pressure of the inspired oxygen and respiratory exchange ratio are 150 mmHg and 0·8, respectively. Points marked with an open square, numbers 1 and 2 and the closed square indicate arterial blood gas values measured on admission to the hospital, at 8 a.m. on 13th February before the tracheotomy, 90 min after the tracheotomy and at 5 p.m. on the same day. From this diagram, it is clear that the tracheotomy increased the alveolar ventilation for this patient.

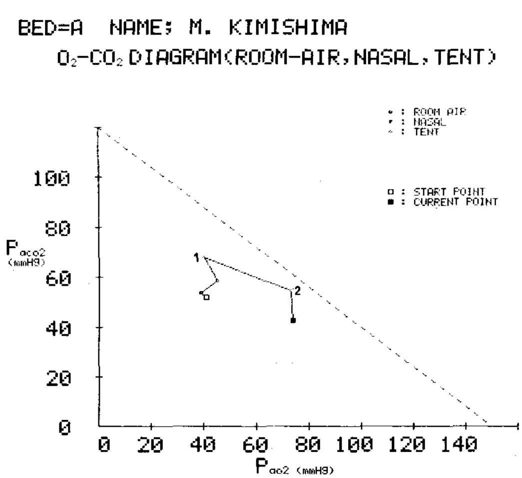


Fig. 6 *The effect of a tracheotomy on the arterial blood gas tensions displayed on an O_2–CO_2 diagram*

Fig. 7 shows trend graphs for on-line data, gathered before and after weaning from a ventilator was carried out. Heart rate HR, respiratory rate RR, tidal volume V_T and minute ventilation volume $\dot{V}_E$ are illustrated. The time span is from 2 to 4 p.m. on 14th February, 1980. Weaning from a ventilator was carried out at 2.45 p.m. (shown by the black arrow). Subsequently, increases in heart rate and respiratory rate and decreases in tidal volume and minute ventilation

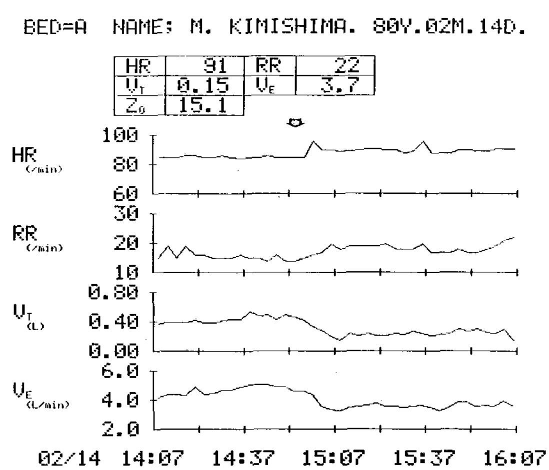


Fig. 7 *Trend graph for the heart rate HR, respiratory rate RR, tidal volume V_T and minute ventilation volume $\dot{V}_E$ on 14th February. At the arrow, weaning from the ventilator was carried out*

volume are seen. The values indicating heart rate HR, respiratory rate RR, tidal volume V_T, minute ventilation volume $\dot{V}_E$ and mean thoracic impedance Z_0 in the table under the patient's name were the latest values in the trend graphs.

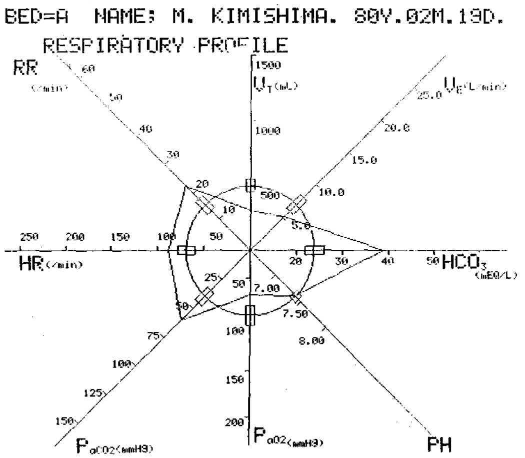


Fig. 8 *Respiratory profile on 14th February, after weaning from the ventilator*

Fig. 8 shows a combined on-line and off-line data graphic display, called a respiratory profile in this study group. The values for the heart rate HR, respiratory rate RR, tidal volume V_T, minute ventilation volume $\dot{V}_E$, bicarbonate ion concentration HCO_3^-, negative logarithm of H^+ concentration (pH) and tensions of oxygen and carbon dioxide in arterial blood paO_2 and $paCO_2$, respectively, are shown clockwise, with circle and rectangle symbols indicating normal values and one standard deviation.

It is clear that the patient is in compensated respiratory acidosis with a decreased tidal volume, minute ventilation volume and arterial oxygen tension, and with an increased respiratory rate, heart rate and arterial carbon dioxide tension.

4 Conclusion

In caring for seriously ill patients, it is, of course, indispensable to gather periodic cardiovascular and respiratory data through out the entire patient history in the intensive care unit. For cardiovascular monitoring, it is now possible to utilise really efficient monitors, such as an arrythmia monitor and a haemodynamic monitor. However, ventilatory monitoring, is carried out by nurses and physicians watching the patients' ventilation and by blood gas analysis with intermittent sampling of arterial and mixed venous blood, as deemed necessary based on observations by trained medical personnel. To achieve a more objective and reasonable evaluation for a patient's ventilatory dynamics and pathophysiology, the development of an appropriate and non-invasive ventilatory monitor has long been desired.

From this viewpoint, the respiratory function monitoring system was developed using the non-invasive ventilatory volume monitor as a key component. The system as presented has several features, as follows:

(i) Ventilatory volume can be measured continuously and non-invasively by the electrical impedance method.

(ii) Together with off-line data, such as blood-gas, blood chemistry and urine volume, on-line data can be gathered periodically and automatically, and filed in floppy disc memory for a long time.

(iii) Using these filed data, various graphic displays can be provided to show the patient's condition easily and accurately.

(iv) This is a microcomputer-based small patient monitoring system, whose performance is as good as that of a minicomputer system.

This system was installed about one year ago and has been tested clinically in a respiratory care unit in Jichi Medical School. According to data obtained from cases involving respiratory failure, it is clear that the introduction of the system into medical practice facilitates a more accurate analysis of respiratory and circulatory pathophysiology for the severely ill patients. Furthermore, it helps to obtain more detailed physical responses to various respiratory and circulatory treatments and to review more systematically the course of the patients' illness.

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