

[54] **AUTOMATIC RESPIRATORY GAS MONITORING SYSTEM**

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[51] Int. Cl.² **A61B 5/08**

[58] Field of Search **128/2.07, 2.08, 2.1 R, 128/2 C, DIG. 29; 73/23.1, 421.5 R, 422, 423**

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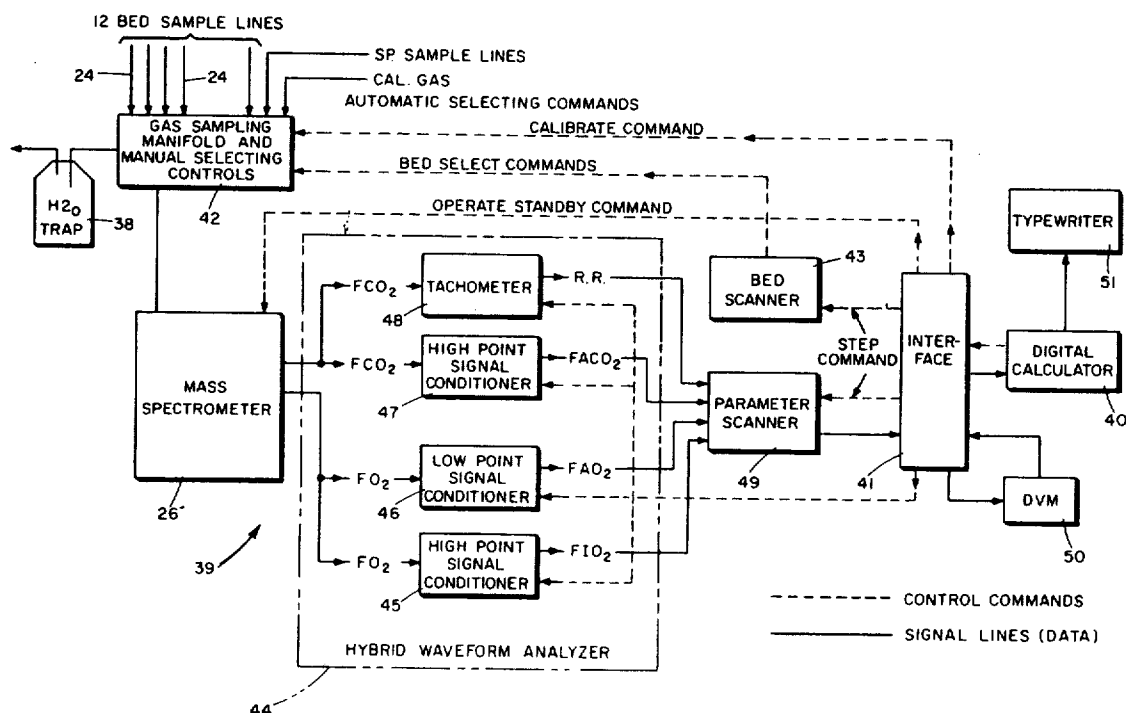
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[57] **ABSTRACT**

An automated system monitors and records vital signs and respiratory gases of each of several patients in an intensive care center by time-sharing the use of a mass spectrometer and hybrid instrumentation under control of an electronic programmable calculator. Automatic measurement is performed and recorded on high and low levels corresponding to inspiratory and peak expiratory values of O₂ and peak expiratory CO₂. Sampled gas waveforms are counted for respiratory rate and the respiratory quotient is computed for each patient. Respiratory gas flow is automatically measured and CO₂ production and O₂ consumption are computed and recorded. This invention is equally applicable to analysis of gases other than respiratory gases.

29 Claims, 9 Drawing Figures



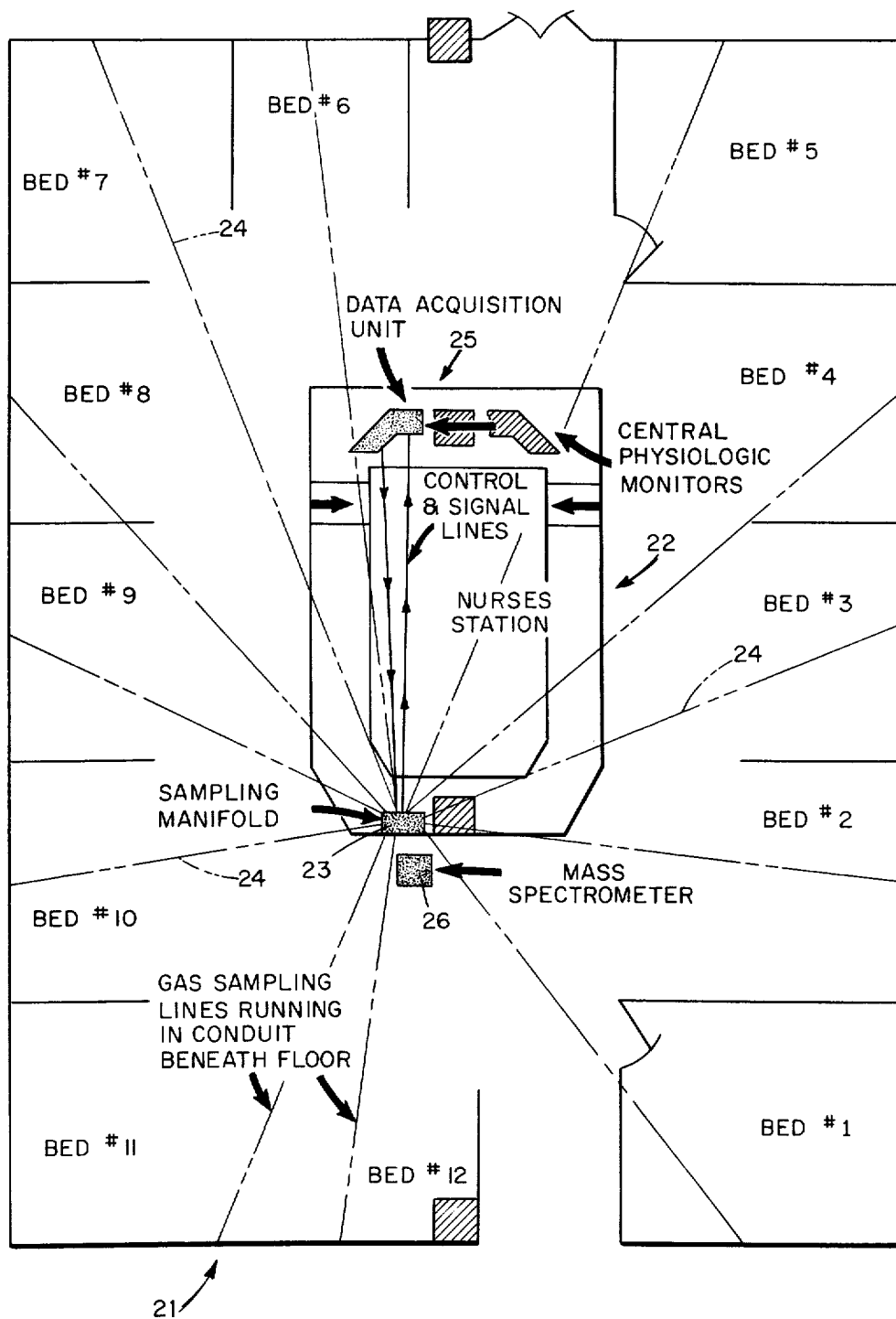


FIG. 1

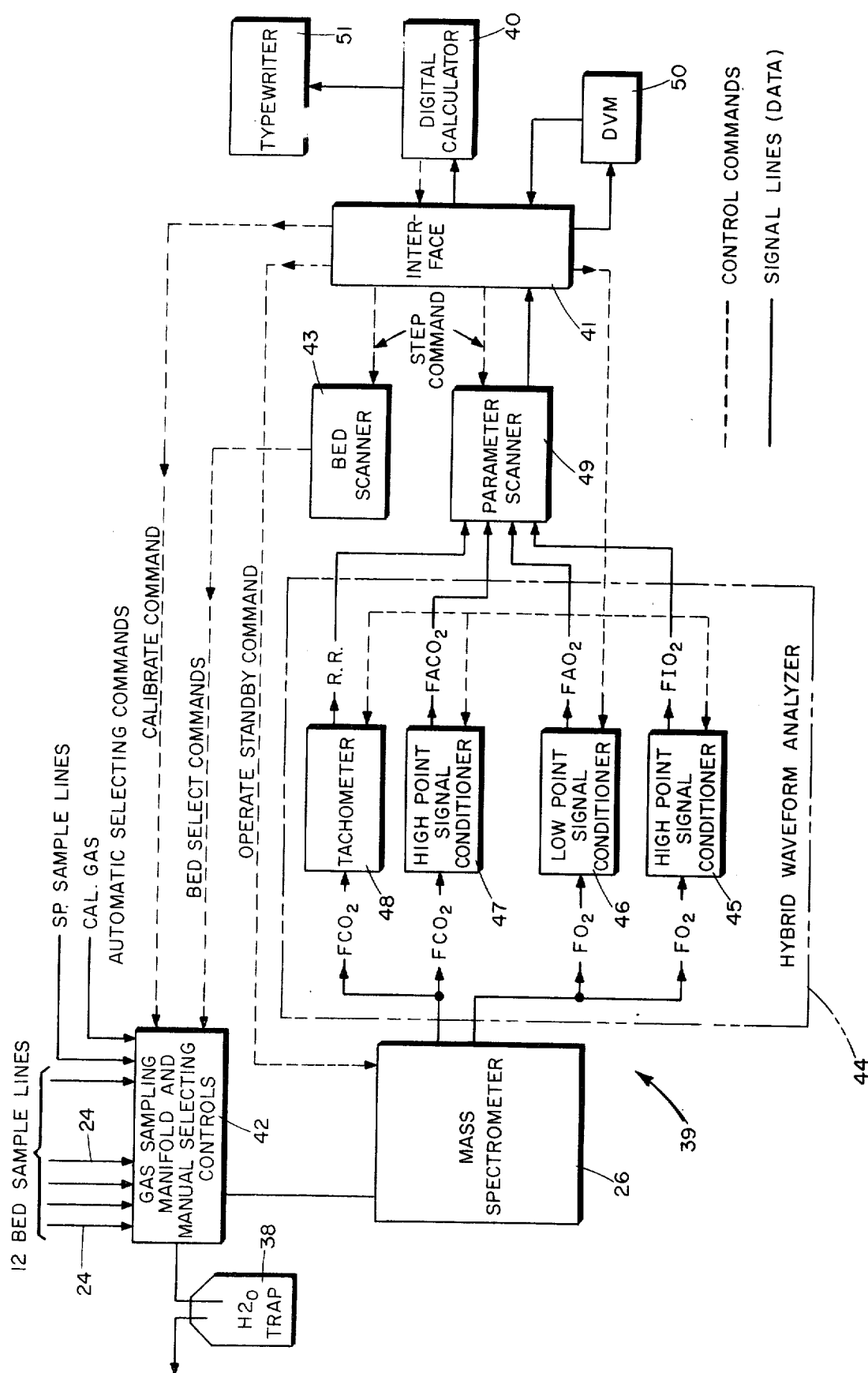


FIG. 2

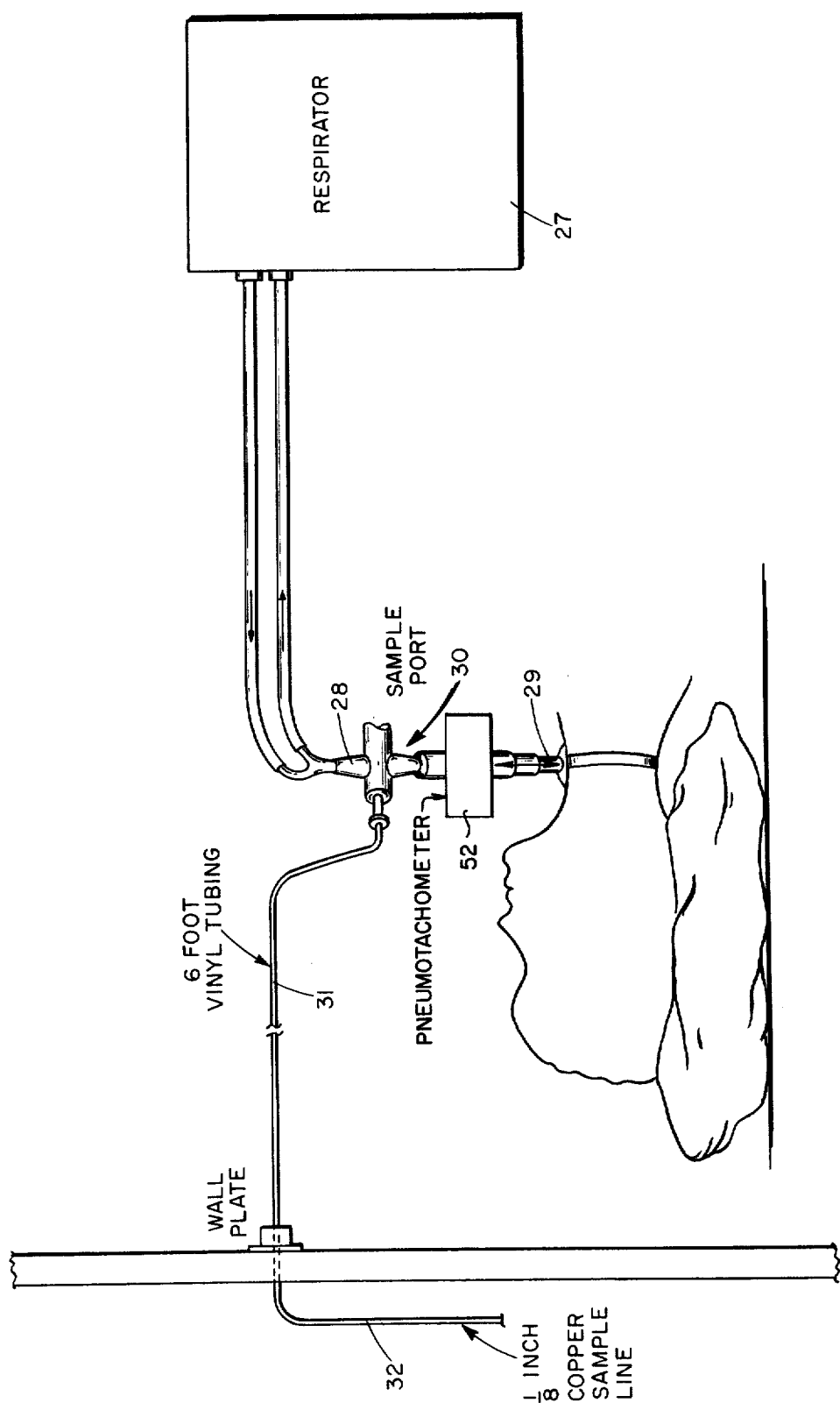
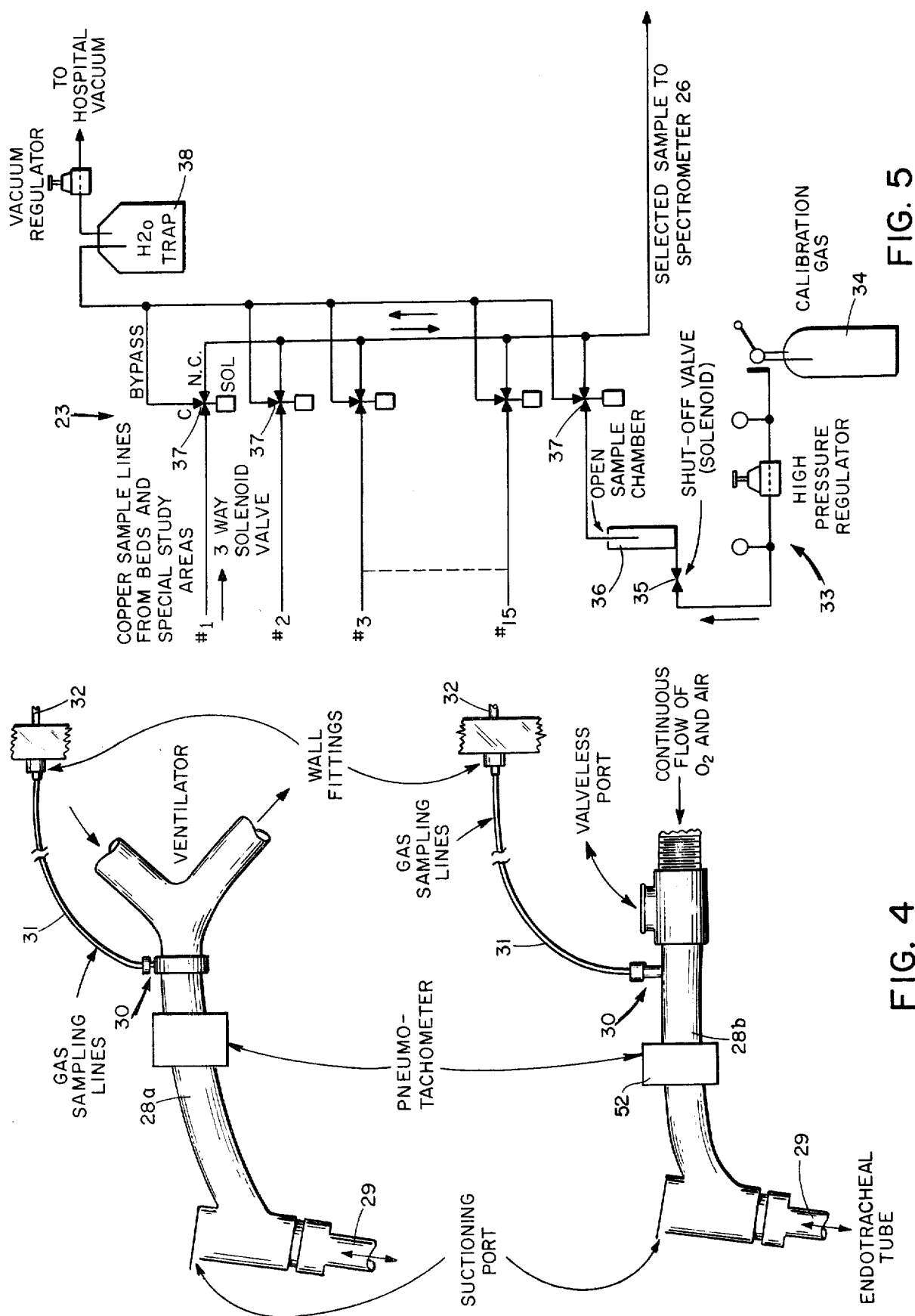


FIG. 3



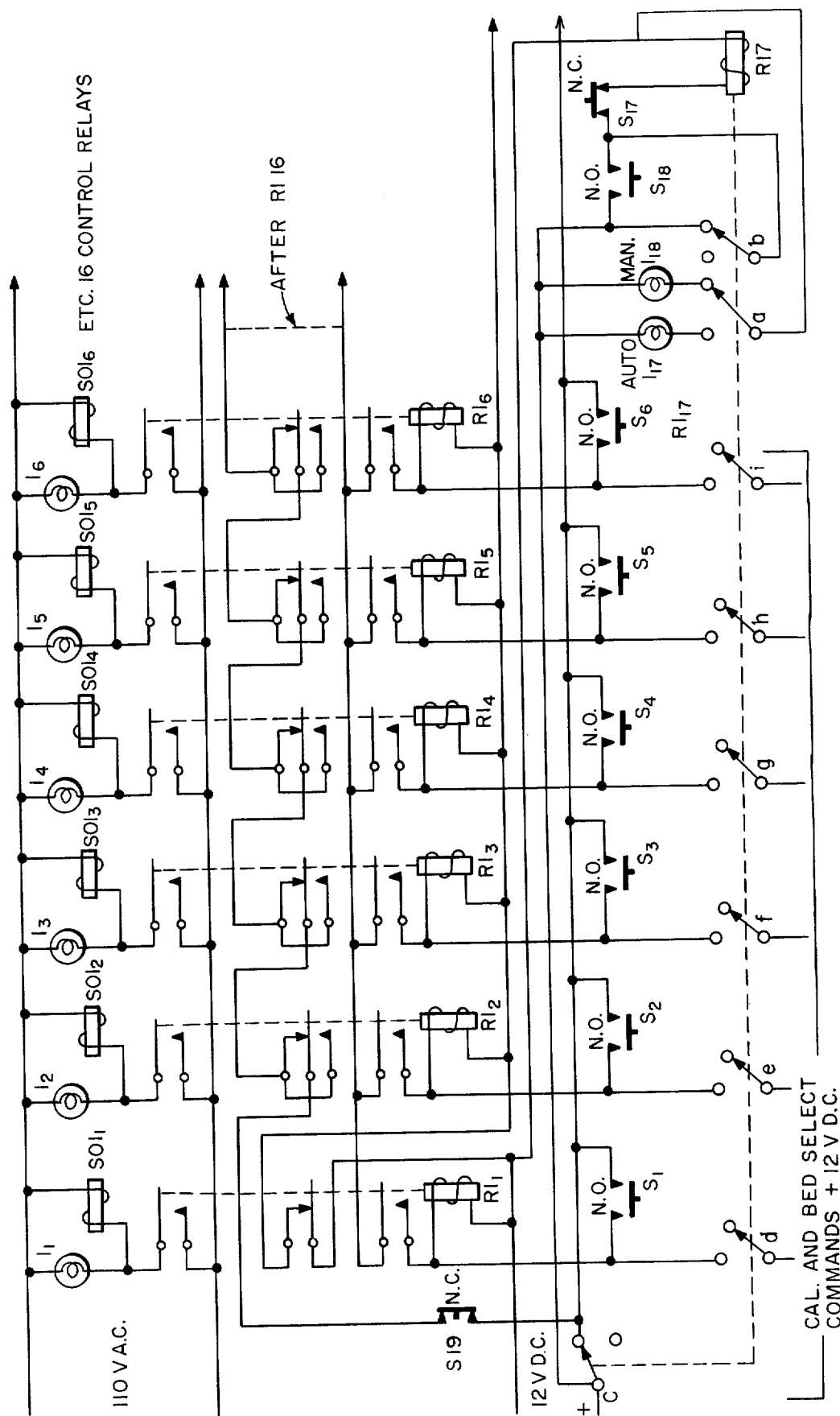


FIG. 6

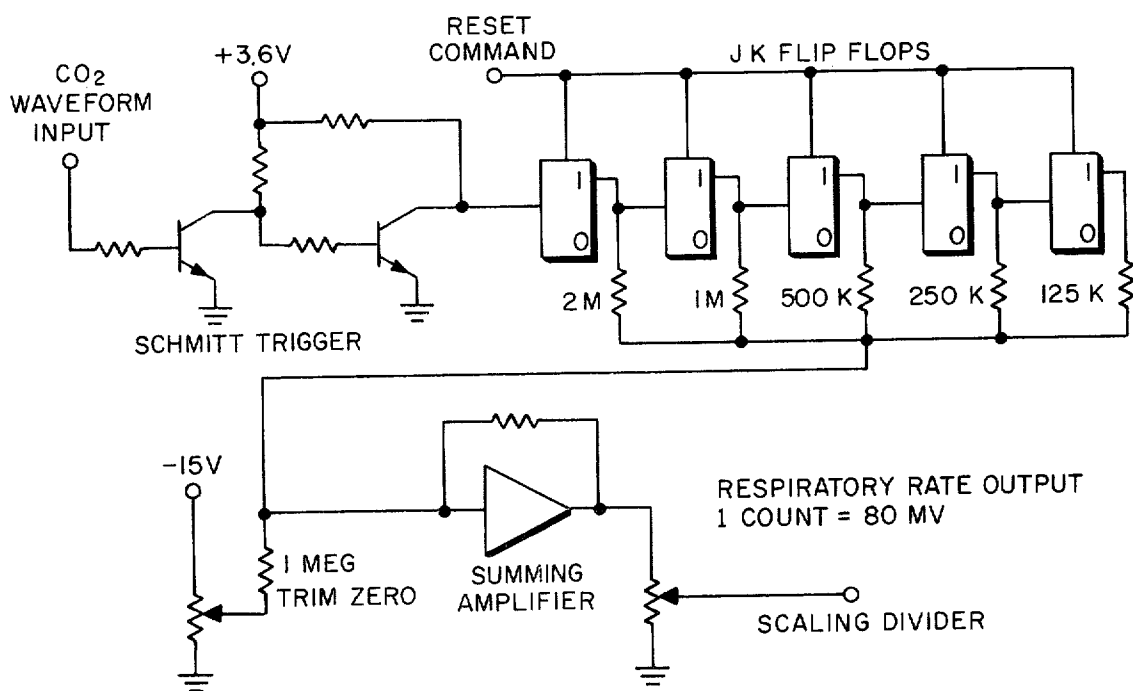


FIG. 7

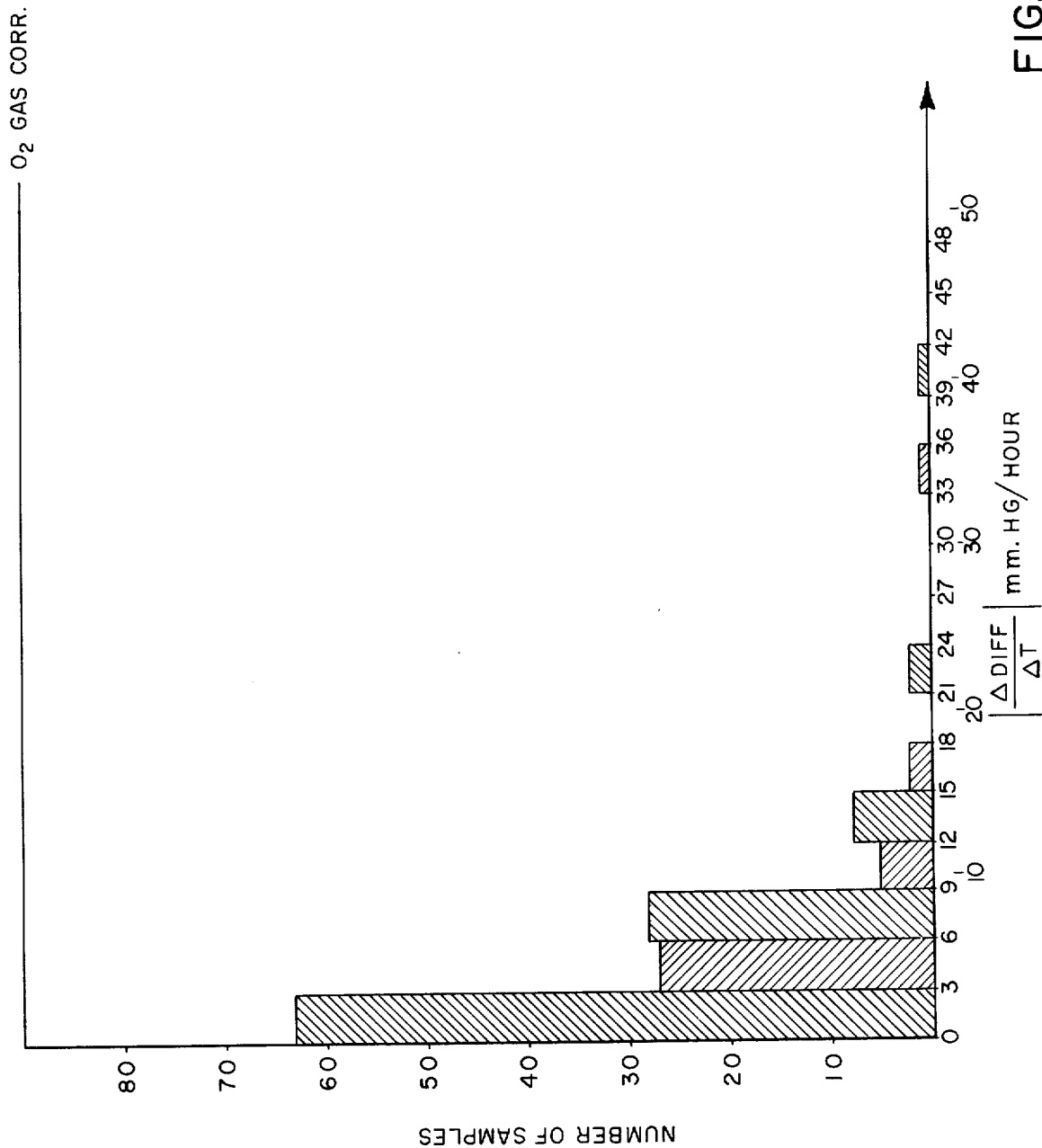
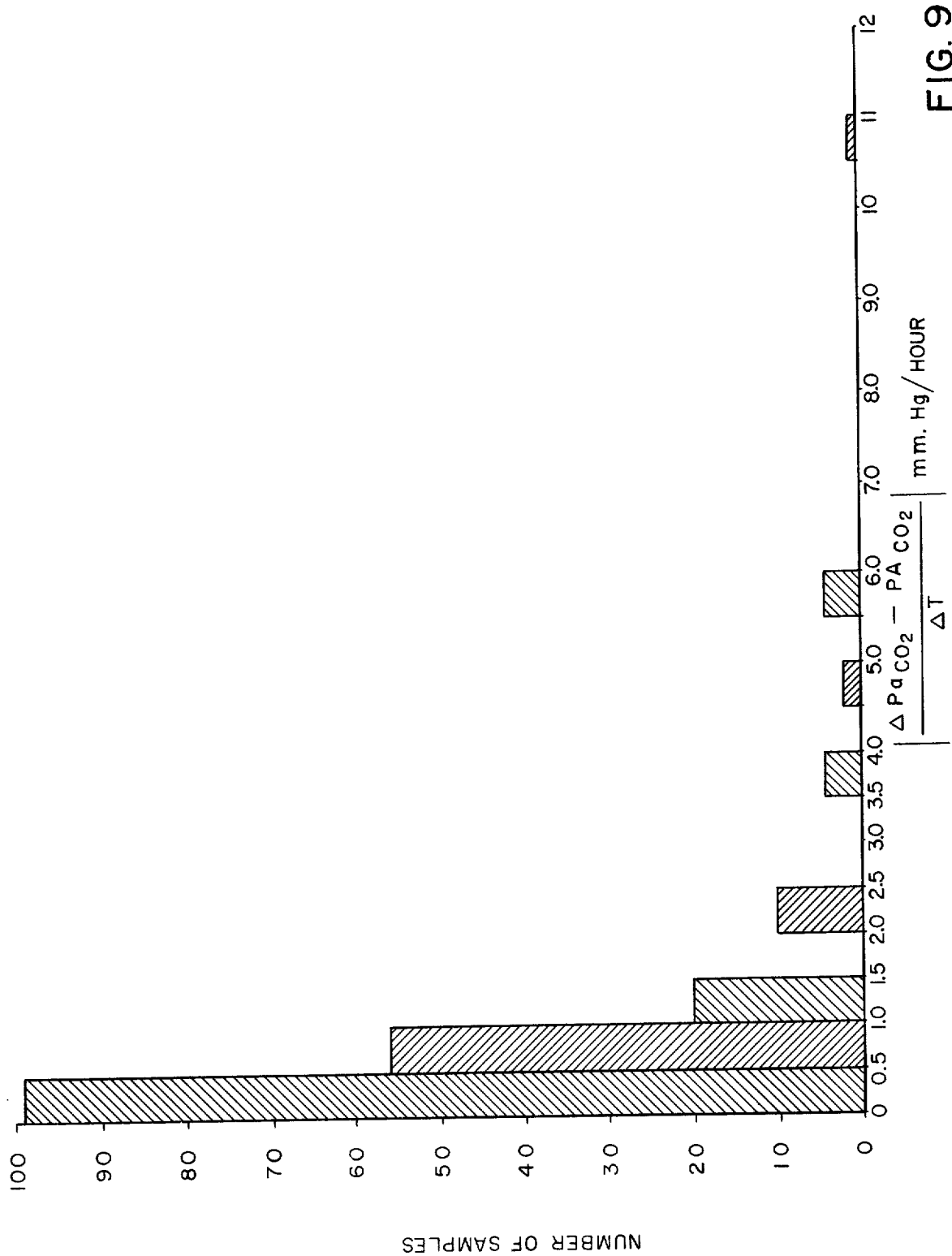


FIG. 8



AUTOMATIC RESPIRATORY GAS MONITORING SYSTEM

FIELD OF THE INVENTION

This invention relates generally to respiratory gas monitoring systems, and more particularly it pertains to a system for automatically monitoring the respiratory gases of each of many patients and thereafter recording various parameters associated with the respiratory gases and vital signs of each of the patients.

DISCUSSION OF PROBLEM AND PRIOR ART

The monitoring of respiratory gases can be of great assistance to a physician treating the critically ill. Unfortunately, instruments capable of doing this job economically in clinical use have heretofore been unavailable. Automated systems are available for the acquisition of data from patients in intensive care units and usually depend upon medium to large scale computers for timing, control and computation. However, the complexity and cost of such systems have limited their practical application.

With a rapidly increasing population and the violent complexities encountered in life today, the number of serious and complicated personal injuries requiring treatment are increasing and getting worse. In many instances, a number of such injured patients require constant surveillance and attention simultaneously. The cost for a medical team and equipment that would be required for each such seriously injured patient would be prohibitive.

Consequently, there is a need for a simplified, economical system which will permit a reasonably limited number of medical personnel to monitor the vital signs and respiratory gases of a number of critically ill patients at frequent intervals.

SUMMARY OF THE INVENTION

It is an object of this invention, therefore, to provide a system for economically and automatically monitoring respiratory gases.

Another object of this invention is to provide a system for monitoring the vital signs of several patients with a time-shared system.

To provide a simplified system for economically monitoring respiratory gases of several patients on a time-shared basis and thereafter recording data of vital signs is yet another object of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects and attendant advantages of this invention will become more readily apparent and understood from the following detailed specification and accompanying drawings in which:

FIG. 1 is a diagrammatical representation of the floor plan layout of a multi-bed intensive care unit with respiratory gas monitoring facilities;

FIG. 2 is a block diagram of the various component parts of an automatic respiratory gas monitoring system embodying certain principles of the invention;

FIG. 3 is a view showing a facility for sampling respiratory gases of a patient;

FIG. 4 is a view showing alternate embodiments of endotracheal attachment devices for obtaining the sampling of respiratory gases;

FIG. 5 is a schematic of a solenoid system which forms a portion of a gas sampling manifold and is used

for selectively connecting patient respiratory-gas and calibration-gas lines to the monitoring and recording system of FIG. 2;

FIG. 6 is a schematic of a relay and switch which also forms a portion of the gas sampling manifold and is used for selective control of the solenoid system of FIG. 5;

FIG. 7 is a schematic of a hybrid circuit which forms a portion of the system of FIG. 2 and which counts the CO₂ waveforms as a measure of respiratory rate;

FIG. 8 is a graph of the frequency distribution of the absolute value of the rate of change of the alveolar-arterial O₂ gradient with respect to time; and

FIG. 9 is a graph of the frequency distribution of the absolute value of the rate of change of the arterial-alveolar CO₂.

DETAILED DESCRIPTION

Referring to FIG. 1, there is illustrated an intensive care unit or trauma center 21 which includes a plurality of patient-bed locations numbered bed No. 1 through bed No. 12. The bed locations are disposed about a centrally located monitoring station 22 which includes the necessary facilities for monitoring respiratory gas samples of patients in the bed locations.

The monitoring facilities include a gas sampling manifold 23 which is linked to each patient-bed location by gas sampling lines 24 located in conduits beneath the floor of the trauma center 21. A data acquisition unit 25 controls the gas sampling manifold 23 to feed respiratory gases of successively sampled patients to a mass spectrometer 26 which rapidly analyzes the waveform of the gas samples and develops analog waveforms in response thereto. The mass spectrometer 26 is a rapid gas analyzer such as, for example, a model MMS-8 available from Scientific Research Instruments Corporation of Baltimore, Md.

The analog waveforms from the mass spectrometer 26 are conditioned by analog filters for high and low levels corresponding to inspiratory and peak expiratory values of O₂ and peak expiratory values of CO₂. CO₂ waveforms are counted for respiratory rate and the respiratory quotient is computed. Respiratory gas flow is measured by an electronic air flow transducer 52 (FIGS. 3 and 4) situated at the patients airway, such as a Fleisch pneumotachometer or an ultrasonic spirometer. The combined data from the mass spectrometer 26 and air flow transducer 52 enables a digital calculator 40 (FIG. 2) to automatically compute CO₂ production and O₂ consumption.

The waveforms developed by the mass spectrometer 26 are ultimately coupled to the data acquisition unit 25 which controls central physiologic monitors to display, for visual observation, the key recorded information relating to respiratory gases and vital signs of the patients in bed No. 1 through bed No. 12.

A nurses' station is located amongst the sampling, analyzing and monitoring facilities to permit a limited number of medical personnel to maintain the trauma center 11.

Referring to FIG. 3, the airway of an intubated patient is connected to a respirator 27 by use of a linking section 28 and an endotracheal tube 29. A sample port 30 is connected to the linking section 28 and facilitates the sampling of the respiratory gases necessary for the monitoring procedure. A vinyl tube 31 of capillary size is connected between the sample port 30, at one end thereof, and one end of a copper tube 32 at the other

end thereof. The vinyl tube 31 and the copper tube 32 combine to form the gas sampling line 24. The other end of the copper tube is connected to the gas sampling manifold 23. The copper tube 32 is $\frac{1}{8}$ inch O.D. and is about 50 feet in length. The vinyl tube 31 is about 6 feet in length. The lengths of the tubes 31 and 32 and the fittings used to make the various interconnections are designed to provide optimum results in a smooth flow of the sampled gases therethrough. A similar arrangement attaches to a mouth piece or face mask to facilitate measurements of extubated patients.

Referring to FIG. 4, there is illustrated two embodiments 28a and 28b of the linking section 28 (FIG. 3) which are somewhat similar except in the portion which is connected directly to the respirator 27 (FIG. 3). The embodiment 28a has a forked ventilator. The embodiment 28b has a single opening for receiving a continuous flow of O_2 and air and also is formed with a valveless port. Each embodiment 28a and 28b has a pneumotachometer, such as the transducer 52, attached thereto to measure the flow rate of gas passing therethrough.

As illustrated in FIG. 5, the gas sampling manifold 23 includes 16 input lines, 12 of which are linked to the bed locations of bed No. 1 through bed No. 12. Three additional lines are connected to other locations in the hospital for sampling gases from a hyperbaric unit, a cardiac catheterization laboratory and a trauma operating suite. The remaining input is connected to a gas calibration facility 33 which includes a supply 34 of calibration gas (5% CO_2 , 50% O_2 , 45% N_2), a solenoid controlled shut-off valve 35 and an open sample chamber 36.

Each of the 16 input lines to the manifold 23 is connected to a three-way, solenoid-controlled valve 37. A normally open port of each of the solenoid-controlled valves 37 is connected, for cleaning purposes, to a hospital vacuum through an H_2O trap 38. The remaining valve arrangement permits selective passage of sampled respiratory gases through the manifold 23 to the spectrometer 26. The vacuum bypass feature also reduces the time required for stabilization to new gas values when switching from patient to patient during the gas sampling period.

Referring to FIG. 2, there is illustrated a block diagram of an automatic respiratory gas monitoring system 39 embodying certain principles of the invention. The system 39 includes a digital calculator 40, such as, for example, a model 370 programmable digital desk calculator available from Wang Laboratories of Tewksbury, Mass. The calculator 40 is equipped with eight program card readers which provide the necessary instructions for operating the system 39.

The command signals are fed from the calculator 40 to an interface 41, such as, for example, a model 379-8 digital interface also available from Wang Laboratories, which then disperses the command signals to the selected facilities of the system 39.

The system 39 also includes the gas sampling manifold 23, which is illustrated in FIG. 5, with manual selecting controls and identified as unit 42. A bed scanner 43 responds to step commands from the calculator 40 and interface 41 to select the particular solenoid-controlled valve 37 (FIG. 5) and, therefore, a particular gas sampling line 24. Instructions for the gas calibration procedure come directly from the interface 41 to the unit 42. Special sample and calibrate gas lines are

also coupled to the unit 42 for purposes previously explained.

The sampled gases are fed to the spectrometer 26 for rapid analyzing. The O_2 and CO_2 analog waveforms developed in response thereto are fed to a hybrid waveform analyzer 44 where the analog waveforms are conditioned for ultimate feeding to the calculator 40. A high point signal conditioner 45 selects the peak of a fractional concentration of the sampled O_2 waveform (FO_2) and develops a signal which represents a fractional concentration of the inspired O_2 (FIO_2).

A fractional concentration of the "valley" of the O_2 waveform (FO_2) is fed to a low point signal conditioner 46 which develops a signal corresponding to an approximation of end-expired O_2 fractional concentration (FAO_2). Similarly, the peak value of expired CO_2 ($FACO_2$) is measured by a high point signal conditioner 47.

The signal conditioners 45, 46 and 47 are, for example, analog filters available from Statham Instruments, Inc., of Oxnard, Calif. The analog filters produce relatively steady voltage levels proportional to the maxima and minima of the output waveforms of the mass spectrometer 26.

The respiratory rate (R.R.) is computed by a tachometer or hybrid circuit 48 in response to receiving a fractional concentration of CO_2 (FCO_2). The circuit 48 is shown in detail in FIG. 7.

The respiratory airflow transducer 52 could be, for example an ultrasonic spirometer model 1007 or model 1009, available from Statham Instruments, Oxnard, Calif. It could also be, for example, a Fleisch pneumotachometer which is also available from Statham Instruments, Oxnard, Calif.

Under the control of step command signals from the interface 41, a parameter scanner 49 scans the conditioners 45, 46 and 47 and the hybrid circuit 48 to feed the respiratory rate, $FACO_2$, FAO_2 , and FIO_2 signals to the interface. These analog signals are then fed to a digital voltmeter 50 where analog-to-digital conversion of the signals is accomplished. The voltmeter 50 could be, for example, a model 4432 digital voltmeter available from Dana Laboratories, Inc., of Irvine, Calif.

The digital signals are then fed through the interface 41 to the digital calculator 40 whereat calculations are made of various respiratory and vital signs information. This information is displayed on a typewriter 51 for monitoring observations by the medical team attending the trauma center 11.

The unit 42 includes a control circuit, as illustrated in FIG. 6, for manual or automatic selection of the solenoid-controlled valves 37 (FIG. 5). A relay coil RI_7 is controlled by momentary manual closing of normally open switch S_{18} to place the associated contacts a through i in the position shown. Also, manual lamp I_{18} is lit. Normally open switches S_1 through S_{16} (only S_1 through S_6 shown) can then be manually and selectively closed to energize associated relay coils RI_1 through RI_{16} , respectively. If for example, the relay coil RI_3 is energized, the solenoid SOI_3 is energized and the related valve 37 is controlled to permit respiratory gases of the patient in bed No. 3 to be sampled and fed to the spectrometer 26 for sample processing. The lamp I_3 is also lit to identify the selected bed.

When normally closed switch S_{17} is momentarily opened, the relay coil RI_{17} is controlled to place the associated contacts a through i in the other position. This conditions the control circuit of unit 42 for auto-

matic control by calibrate and bed select commands from the interface 41 and the bed scanner 43. The relay coils RI₁ through RI₁₆ can now be controlled automatically and, if desired, sequentially.

The hybrid circuit 48 is illustrated in detail in FIG. 7 and includes a Schmitt trigger which is fired at specific voltage levels of each CO₂ waveform input. The resulting pulse is fed to the input of a binary counter composed of five J-K flip-flops. The binary digital count is converted back to an analog voltage level by a summing amplifier with gains proportional to the magnitudes of the binary digits. In operation, the counter is reset to zero, then counts expirations for 23 seconds. The count is then read as an analog voltage and ultimately multiplied by 60/23 to obtain breaths per minute.

The bed scanner 43 could, for example, be a multiple-deck stepping switch with the associated stepping coil being controlled by the calculator 40 through the interface 41. The stepping switch control can thus facilitate the ultimate control of the solenoids SOI₁ - SOI₁₂ for the sequential gas sampling procedure through the control circuit of FIG. 6 and the bed select commands from the calculator 40.

The parameter scanner 49 could also be a decked stepping switch with the associated stepping coil being controlled by the calculator 40 through the interface 41. Four terminals of the stepping switch are connected to the conditioners 45, 46 and 47 and the hybrid circuit 48, respectively, to facilitate the feeding of the various analog waveforms the digital voltmeter 50.

Each contact of one deck of the multiple deck stepping switch could be connected to a different junction point between adjacent series-connected resistors of a chain of series-connected resistors which are connected to a potential source.

The number of junction points corresponds to the number of bed locations with a different analog potential appearing at each junction point to identify the selected bed location for patient gas sampling. A single-pole, double-throw switch is connected between each terminal of the stepping switch and the associated junction point so that the terminal can be selectively connected to ground if there is no patient located at the particular bed location. The particular analog potential can be fed to the calculator 40 for printout on the typewriter 51 to identify from which patient the sampled gases are taken.

Other decks of the multiple deck switch could be connected to transducers at bedside to pick up the patient's temperature, pulse and other vital intelligence. This information is selectively fed to the calculator 40 by use of additional terminals on the parameter scanner 49 and ultimately appears on the printout of the typewriter 51.

Under the automatic control of the program, the calculator 40 each hour enters a sequence wherein the spectrometer 26 is placed in an "operate" mode for a 2-minute warmup and stabilization period. Each occupied bed is sampled sequentially for 20 seconds at 1-minute intervals. Prior to each bed reading, the calibrating gas is read and corrections made for changes in calibration. Readings from the analog signal conditioners 45, 46 and 47 and the hybrid circuit 48 which functions as the respiratory rate counter. Calculations are made and printed out along with time, hour and minute, and bed identification number.

The print-out includes:

- a. maximum FCO₂ (PACO₂ and FACO₂)
- b. minimum FO₂ (PAO₂ and FAO₂)
- c. maximum FO₂ (FIO₂)
- d. respiratory rate (R.R.), and
- e. respiratory exchange ratio (R_E),

where

$$R_E = \frac{PACO_2 (I - FIO_2)}{PIO_2 - PAO_2 - (PACO_2 \times FIO_2)}$$

- f. tidal volume (V_T)
- g. minute ventilation (V_E)
- h. CO₂ production (VCO₂)
- i. O₂ consumption (VO₂)

In the above print-out display,

FCO₂ is a fractional concentration of CO₂;

PACO₂ is the pressure of peak expired CO₂;

FACO₂ is the fractional concentration of peak expired CO₂;

FO₂ is a fractional concentration of O₂;

PAO₂ is the pressure of peak expired O₂;

FAO₂ is the fractional concentration of peak expired O₂;

FIO₂ is the fractional concentration of peak inspired O₂, and

PIO₂ is the pressure of peak inspired O₂.

At the completion of the sampling sequence, the spectrometer 26 is placed on standby status.

As previously noted, the calculator 40 may be overridden manually by switch S18 which energizes relay coil R17 so that the switches S₁ through S₁₆ can control the individual solenoid valves SOI₁ through SOI₁₆, respectively, may be actuated at any time for any length of time.

The calculator programming permits spot readings of any selected sample line 24 at 1-minute intervals at the option of clinical staff, in addition to automatically initiated hourly readings from all patients in the unit. The data obtained in this spotreading made is still automatically calibrated, calculated and printed as in the hourly sequence.

There is shown in FIG. 8 the frequency distribution of the absolute value of the rate of change, with respect to time, of the alveolar-arterial oxygen (A-aO₂) gradient which has a distinct relationship to PAO₂, as would be anticipated in patients with large intrapulmonary shunts. This distribution was tabulated from 137 pairs of sequential measurements in 16 patients. The data were restricted to sequential measurements such that PAO₂ was not altered more than 100 mm. Hg. during the interval between measurements.

There is shown in FIG. 9 the frequency distribution of the absolute value of rate of change in the arterial-alveolar CO₂ (a-ACO₂) gradient. The distribution is of a sample of 203 sequential pairs of readings from 15 patients. The data were restricted to samples measured not more than 24 hours apart. A large CO₂ gradient is seen primarily with a large alveolar dead space.

Obviously many modifications and variations of the present invention are possible in light of the above teachings. It is, therefore, to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A system for monitoring respiratory gases, which comprises:

means for withdrawing respiratory gases from the airway of at least one patient,

means for rapidly analyzing the withdrawn gases and for developing analog waveforms in response to the analyzation of the withdrawn gases where the waveforms are representative of fractional concentrations of the withdrawn gases,

means responsive to the developed analog waveforms for developing voltage levels proportional to the maxima and minima of the developed analog waveforms where the maxima and minima of the waveforms are representative of monitored values of inspired and expired respiratory gases, and means responsive to the developed voltage levels for displaying in visual form an indication of the maxima and minima values.

2. The monitoring system as set forth in claim 1 which further comprises means for automatically controlling the withdrawing of the patients respiratory gases at selected intervals.

3. The monitoring system as set forth in claim 1 wherein said withdrawing means further comprises:

means for withdrawing the respiratory gases of a plurality of patients to sample the respiratory gases, and

means for connecting the withdrawn gases of each patient, independently of the withdrawn gases of the remaining patients, to the rapid analyzing means.

4. The monitoring system as set forth in claim 3 which further comprises means for automatically controlling the connecting means to selectively connect the withdrawn gases of each patient to the rapid analyzing means so that the withdrawn gases of only one patient are connected to the rapid analyzing means at any given instant.

5. The monitoring system as set forth in claim 4 which further comprises means for feeding a calibrating gas to the rapid analyzing means to calibrate the analyzing means prior to analyzing of the respiratory gases of each patient.

6. The monitoring system as set forth in claim 1 which further comprises means responsive to the development of an O₂ waveform from the rapid analyzing means for counting the respiratory rate of the patient whose respiration gases are being sampled and monitored.

7. The monitoring system as set forth in claim 1 wherein the analyzing means is a mass spectrometer.

8. The monitoring system as set forth in claim 1 which further comprises means for simultaneous measurement of respiratory gas flow.

9. The monitoring system as set forth in claim 8 wherein the means for measurement of respiratory gas flow is a pneumotachometer.

10. The monitoring system as set forth in claim 8 wherein the means for measuring respiratory gas flow is a spirometer.

11. A gas monitoring system, which comprises:

a plurality of gas sampling lines each of which is connectable to the airway of a respective one of a plurality of gas systems whose gases are to be sampled, the systems being independent of each other, means for rapidly analyzing the sampled gases and for developing waveforms in response to the analyzation of the sampled gases,

means connected in each of the sampling lines for opening and closing the lines to permit and prevent, respectively, flow of the sampled gases there-through,

means for coupling each of the sampling lines to the analyzing means,

means for selectively operating the opening and closing means to permit the selective linking of each of the sampling lines with the analyzing means independent of the remaining sampling lines, and means responsive to the developed waveforms for developing signal levels proportional to and representative of monitored values of the sampled gases.

12. A gas monitoring system as recited in claim 11, which further comprises means responsive to the developed signal levels for displaying in visual form an indication of such levels as a representation of the monitored values of the sampled gases.

13. A gas monitoring system as recited in claim 11, which further comprises means for automatically and periodically controlling the operating means to permit automatic monitoring of each of the plurality of gas systems independent of the remaining gas systems.

14. A gas monitoring system as recited in claim 13 wherein the controlling means includes:

means for selectively scanning the opening and closing means, and

means for producing step command signals to operate the scanning means in a predetermined manner to monitor the sampling lines as desired.

15. A gas monitoring system as recited in claim 11, wherein the analyzing means is a mass spectrometer.

16. A gas monitoring system as recited in claim 11 wherein the opening and closing means includes a plurality of valves each of which is connected serially in a respective one of the sampling lines.

17. A gas monitoring system as recited in claim 16, wherein:

the operating means includes a plurality of solenoids each of which is connected to a respective one of the valves, and

electrical control means for selectively operating the solenoids independently of the remaining solenoids to permit selection of one of the sampling lines.

18. A gas monitoring system as recited in claim 17, which further comprises means for automatically operating the electrical control means in a predetermined manner to selectively operate the solenoids in a selected sequence so that sampled gases of the plurality of systems are fed to the analyzing means in a predetermined sequential manner.

19. A gas monitoring system as recited in claim 11 wherein the developed waveforms are analog waveforms and the signal levels developing means includes a plurality of analog filters which produce steady voltage levels proportional to maxima and minima levels of the waveforms developed by the analyzing means.

20. A gas monitoring system as recited in claim 11 wherein the analyzing means includes means for analyzing sampled gases which include inspired O₂ gases and expired CO₂ gases, and the waveforms developed by the analyzing means are analog waveforms representative of fractional concentrations of the inspired O₂ gases and expired CO₂ gases.

21. A gas monitoring system as recited in claim 20 wherein the signal levels developing means includes a plurality of signal conditioners which in response to the analog waveforms developed by the analyzing means develop signals representative of fractional concentrations of inspired O₂ gases, end-expired O₂ gases and

expired CO₂ gases.

22. A gas monitoring system as recited in claim 21 wherein the signals developed by the signal conditioners are in analog form, and which further comprises:

means responsive to the analog signals developed by the plurality of signal conditioners for converting the analog signals to digital signals representative of fractional concentrations of inspired O₂ gases, end-expired O₂ gases and expired CO₂ gases, and means for scanning the plurality of signal conditioners and for selectively coupling the analog signals of the signal conditioners to the converting means.

23. A gas monitoring system as recited in claim 22, which further comprises means for automatically controlling the operation of the scanning and selective coupling means to permit the monitoring of the signal conditioners in a predetermined manner.

24. A gas monitoring system as recited in claim 21 wherein each of the plurality of signal conditioners are analog filters which produce steady voltage levels proportional to maxima and minima levels of the waveforms developed by the analyzing means.

25. A gas monitoring system as recited in claim 20, which further comprises means for computing the respiratory rate of each of the plurality of gas systems in response to the expired CO₂ fractional concentration waveforms developed by the analyzing means.

26. A gas monitoring system as recited in claim 25, wherein the computing means includes:

a circuit operable at specific levels of each expired CO₂ waveform for producing an output pulse representative of each respiration of the gas system being analyzed,

a binary counter responsive to each pulse produced by the circuit for producing successive counts in binary digital form, and

a summing circuit responsive to the binary digital counts of the counter for summing the counts and developing an analog voltage level representative of the respiratory rate of the gas system being analyzed.

27. A gas monitoring system as recited in claim 11 which further comprises means located in each of the sampling lines of each of the gas systems for measuring the flow of respiratory gases through the sampling line.

28. A gas monitoring system as recited in claim 11 which further comprises means for indicating which sampling line is linked to the analyzing means at any given instant.

29. A gas monitoring system as recited in claim 11 wherein the signal levels developed by the signal levels developing means are in analog form and which further comprises means responsive to the developed analog signal levels for converting the analog levels to digital signals representative of the monitored values of the sampled gases.

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