AN ELECTRO PNEUMATIC ANAESTHESIA VENTILATOR FOR
CONTROLLED VENTILATION: DESIGN AND DEVELOPMENT

Jaspreet Kaur1*, Jagdish Kumar1, Dr. Pawan Kapur1 and Dr. B S Sohi2

1 Central Scientific Instruments Organisation, A Lab. of Council of Scientific and Industrial Research, Sector-30, Chandigarh, India
2 Surya Group of Institutions

*Corresponding Author
Email: jaspreet_k123@rediffmail.com
Phone: 0172-2657811, 2651831 extn. 473

ABSTRACT
Anaesthesia ventilators are used when artificial ventilation needs to be maintained for a long time to support human breathing at different stages of treatment and pathologies. These are sophisticated equipment with a large number of controls in maintaining proper and regulated breathing activity. Breathing oxygen from anaesthesia delivery system is stored inside a rubber bellow for delivering to the patients by squeezing the bellow with controlled amount of exerting pressure on the rubber bellow. Presently available ventilators use an electro-pneumatic system to control flow, pressure and volume of supplied and extracted air. In this paper, authors have described design of a versatile, inexpensive and fully engineered prototype of anaesthesia ventilator. It is a pneumatically driven, electronically controlled time cycled system used for performing all functional requirements of respiratory support. In this ventilator, a set volume of gas is delivered to the patient in a predetermined period of time and the same is exhaled by the patient over another interval of time constituting a complete cycle of respiration. The developed device controls all parameters of breath such as tidal volume, respiration rate, I:E ratio and inspiratory flow rate.

KEY WORDS
anaesthesia ventilator, airway pressure, piezoresistive pressure sensor, microcontroller, graphical display, tidal volume, respiration rate, inspiratory flow rate, minute volume

1. Introduction
Ventilators of different types in functional characteristics and construction have been used in the operation theatres and intensive care units to deliver mechanical ventilation to the lungs during anaesthesia. Various ventilatory modes [continuous mandatory ventilation (CMV), intermittent mandatory ventilation (IMV), assist-control ventilation (A/C), pressure support (PS) and continuous positive airway pressure)] were evolved in present designs to support breathing. Available designs of ventilators do not have provision of setting ventilatory parameters using touch sense control knobs. Use of touch sense knobs enhance attention of anesthetist on patient breathing comfort and replace multiple components needed for front panel of existing designs of ventilators.

The basic functional requirements of a ventilator is to deliver specific volumes of gases like O2, air, N2O and volatile agents at a desired rate to the patient through an anesthetic circuit while maintaining a set respiration rate value. It provides air/oxygen with a force that inflates the patient lungs and also determines the respiratory cycle. Further, it decides when to stop the process of inflation and start the process of expiration and vice versa. While delivering a breath, the ventilator controls all parameters of the breath such as tidal volume, flow rate, respiration rate, I:E (inspiration time to expiration time) ratio etc.

The advancement of technology has resulted in the transition from manual to automated methods in this area has increased analysis efficiency. Developments in electronics and embedded system programming techniques have made it easier to carry out accurate analysis, monitoring and measurement of different parameters such as tidal volume (TV), respiration rate (RR), inspiratory flow rate (IF), airway pressure (AP) etc. leading to availability of more information to the medical experts about the patient.

In this paper authors have described the design and development of a microcontroller based electro pneumatic ventilator used for controlled mandatory ventilation. The drive system includes a gas supply i.e. oxygen at 50 – 70 psig. The ventilator has three basic subsystems - bellow system supported by pneumatic driving components; microcontroller based control system for ventilator parameter control and a closed rebreathing circle absorber type patient circuit.
2. Materials and methods

2.1 Technique and working principle of the Instrument-

The drive gas is controlled with the use of a solenoid valve, a gas inlet valve and a flow controlled valve (Fig. 1). A gas drive chamber is connected via a bidirectional polyvalve. This valve also takes care of the release of the remaining driving gas in the bellow jar during the expiratory time period. It is found that the drive gas is needed to be supplied at a high pressure of 60-70 psig.

2.2 Microcontroller based Control System

System design is based around 80C31 microcontroller (Fig. 2) connected to other devices through address bus, data bus, and control bus. A 40 characters X 4 lines alphanumeric LCD display is used for displaying various set parameters such as TV, RR, IF calculated parameters such as I:E ratio, MV and measured parameters AP and flow. For control of the breathing, the three independent control parameters i.e. respiratory rate, tidal volume and inspiratory flow are set through the control panel of the instrument. Each of these parameters has a knob which is sensitive to touch. As soon as any one of these knobs is touched, the alphanumeric display of that parameter along with its unit is displayed on the LCD module for identification of the control parameter being handled. The module displays the current online value of the setting being changed or maintained by the control knob. Block diagram of the hardware system is as shown in Fig. 3.

Multiplexer selects and presents one input at a time followed by Analog to digital converter AD574 which converts the analog input into the digital form.

Microcontroller gives at its output a precise timing pulse with a repetition rate set exactly at the control panel. This control circuit also releases an electrical signal proportional to the set tidal volume to control the final flow control valve of the ventilator proportionately.

The time duration of the inspiration & expiration part within a respiratory cycle is also calculated by the controller to maintain an I:E ratio for respiration. The microcontroller calculates the inspiration time by dividing the set tidal volume value by the set inspiratory flow rate. The last stage of the system will be digital to analog converter because digital output of the microcontroller cannot be employed for the direct control of the next stage.

Various safety features have been incorporated in the system with several alarm buzzers along with the message display through the alpha-numerical LCD.
2.3 Airway pressure measurement system

The parameter AP is monitored through a LED bargraph display using piezoresistive miniaturized pressure sensor (Fig. 4). Also, as an additional facility, real time AP waveform is displayed on a separate LCD graphic display unit. By this, it is possible to realize the rise and fall of air pressure over a breathing cycle. The sensor selected has a pressure range of 0-5 psig. Pressure applied to the diaphragm causes change in the resistance of the resistors and a voltage proportional to AP is obtained (0-17 mV). The signal is amplified by low thermal and noise drift, high input impedance and accurate closed loop gain amplifier.

Output of filter is amplified again and passed to a buffer known as voltage follower. Use of unity gain buffer amplifier reduces loading effect in measurement system. After calculating analog value of AP, it is converted in digital form by using 12-bit A/D converter. Microcontroller processes digital data and displays on LCD in graphical form. Measurement and design requirements are as follows: pressure range, 0-120 cm of H2O; response time of sensor, 10 millisecond; resolution, 7 cm of H2O; time period (X-axis), 1-15 sec; maximum frequency of signal, 1 Hz; output signal of pressure transducer, 0-17 mV; output signal from instrumentation amplifier, 0-1.25 V. Several audio and visual alarms have been added to AP measurement system so as to make the system safe and failure proof to the extent possible. Main alarm conditions are AP high and AP low.

2.4 Flow measurement system

This system accurately measures airflow for anaesthesia ventilator in the required range of 0-70 l/m. Thermistor based hardware design associated with graphical approach has been deployed successfully leading to simplicity of design, dynamic stability and fast response time.

In this system, thermistor works as a separate arm of a Wheatstone bridge. To self heat, thermistor is subjected to power levels that vary thermistor’s body temperature above environmental surroundings. As environment changes, bridge becomes unbalanced, indicating change in flow, which is then calibrated.

The module is adapted to be connected to a source of gas. The module also includes a fixed volume pipe connected to gas source. Mass flow controller has been used to control gas flow within the chamber.
Signal processing circuit (Fig. 5) consists of a Wheatstone bridge, one arm of which is thermistor and other arms are fixed standard resistances. Bead of thermistor is placed in air medium, whose flow is to be measured. Output of thermistor-based circuit is a voltage, which varies directly with gas flow passed through the tube. Bridge output is amplified and is converted into digital value by a 12-bit analog to digital converter. Microcontroller performs calculations on these digital values and results are displayed on LCD.

2.5 Breathing Circuit

The ventilator design is for use in closed circuit with CO$_2$ circle absorber. The gas from anaesthesia machine is continuously in circulation. The designing of breathing circuit is such that the gas flow for inspiration and expiration to and from the bellow is through on connection tubing. The inspiratory limb and expiratory limbs take up inspired and expired gas respectively. The soda lime canister takes up expired gas and releases refresh gas after absorption of CO$_2$. For this purpose of unidirectional flow of gas inspiration and expiration phase, a set of poly valves & one way valves have been incorporated.

2.6 Gas Inlet Valve

A gas inlet valve is required for primary entry of gas into the pneumatic system.

2.7 Bellow System

The bellow system designed has five parts: Bellow transport cover, bellow structure (rubber), bellow base, distributor, Pop off valve. The breathing gas entry and exit to the rubber bellow takes place through a single port where inspiratory flow of gas is in a direction out of the bellow & the expiratory flow of gas is directed towards the bellow when the expired gas is recycled through a soda lime purifier being put in a poly valve based circle absorber circuit. The inspiratory and expiratory limb in the patient circuit is a part of the circle absorber.

3. Safety Considerations and Alarms

It is imperative to ensure the safety of the patient while ventilator is under operation. To this end several measures have been incorporated into the system. Besides indication to the operator or to the anesthetist about the abnormal behavior, there is display in LCD as well as an audio alarm indication. The various alarms incorporated in the anaesthesia ventilator are:

- **Power fail alarm**: An alarm sounds on failure of supply of AC power.
- **Set volume not delivered alarm**: Whenever tidal volume delivered is found to be less than set volume, this alarm sounds.
- **Low Oxygen supply pressure alarm**: When the pressure of the driving gas falls below 40 psig, the drive system does not work properly and hence alarm is required.
- **Low airway pressure alarm**: If the airway pressure does not reach 6 cm of H$_2$O column after two or three ventilator cycles, this alarm sounds.
- **Actual I:E less than dial setting alarm**: When the settings are adjusted in such a way that the required inspiratory time to expiratory time ratio falls beyond limits of I: E between 1:1 and 1:4, this alarm sounds.
- **High and Low Minute Volume**: When calculated MV is greater than or less than set values these alarms sound. The values for set MV High and low alarm are programmable.
- **High and Low Airway Pressure**: When actual AP is greater than or less than set values of high or low AP these alarms sound. The values for set AP High and low alarm are also programmable.

4. System Software

The layout of the steps followed in the development of the software of the instrument has been provided in the flow chart shown in Fig 6. System software is user friendly. Many advance features have been incorporated in the...
software for fast and robust operation. System software is stored in the system EPROM.

5. Results and Discussion

The system, fabricated and thoroughly tested for three control parameters, was found to be working satisfactorily giving accurate results. Its noise immunity has been observed to be excellent as it works in harsh environment. LCD module helps to monitor tidal volume, respiration rate, and inspiratory flow rate without going through complex sequential operations, thus making the system ideal for ventilators. The LCD module used here has got the facility of backlight thus making this system ideal for instruments working in dark environment. Specifications of the machine performance are as follow: Control Specifications:- tidal volume: 50-1600ml, inspiratory flow: 4-100 l/min, respiration rate: 4-60 b/min; Monitoring:-tidal volume, minute volume, inspiration Flow, FiO2; Touch sense display:- respiratory rate, inspiratory Flow, respiration rate; airway pressure : 20 to + 120cm H2O with bar graph indicator and real time graphical display. The system & safety features have several alarm buzzers along with the message display through the Alpha-numerical LCD. The touch sense parameters i.e. tidal volume (50-1600 ml), respiration rate (4-60 b/min) and inspiratory flow rate (4-100 l/min) are working satisfactorily for the specified range suitable for anaesthesia ventilators. Results for these parameters performance are tested with the help of a standard QA-VTM ventilator tester for different settings of tidal volume, respiration rate and inspiratory flow and derived parameters viz. minute volume, inspiration time, I:E ratio and other measured parameters i.e. airway pressure.

6. Conclusion

Ventilator is critical equipment in OT and precautions must be taken that ventilator system is highly reliable. Proper ventilation accurately restores levels of oxygen and carbon dioxide in the blood. When combined with proper respiratory hygiene, it can prolong life considerably. The developed system meets all the requirements.

In this system, the programming, reading, and reporting operations are easy and user friendly. The instrument is provided with control knobs which facilitates quick change from one function to another and setting of parameters which can be monitored on LCD with both alphanumeric as well as graphics capabilities without going through complex sequential operations. Microcontroller based system for ventilator parameter control has monitoring and display facility of desired and observed parameters of respiration with all necessary safety and alarm indicators to keep the patient safe and risk free. The instrument has been tested with standard ventilator tester QA-VTM and results have been found to be satisfactory. Calibration of the system is reproducible. The instrument developed is universally useful for small and big hospitals, and nursing homes.

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References

Figure 6. Flow diagram of software for Anaesthesia Ventilator