A VARIABLE WAVEFORM VENTILATOR

BY

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SUMMARY

A patient ventilator, which is in effect a variable waveform gas flow generator, is described. This ventilator will produce a large number of selected inspiratory flow waveforms, will accurately control the inspiratory/expiratory time, and will change the volume delivered without changing the flow waveform or the inspiratory/expiratory timing.

There have been a number of studies of the physiological effects of different tracheal pressure wave patterns in patients requiring artificial ventilation with intermittent positive pressure (IPPV) (Werko, 1947; Cournand et al., 1948; Maloney et al., 1953; Watson, 1962a, b; Bergman, 1963, 1967; Grenvik, 1966; Auchinloss and Gilbert, 1967; Robinson, 1967; Herzog and Norlander, 1968; Adams et al., 1970). These studies have in some instances used specially designed ventilators which could vary the pressure wave pattern (Clutton-Brock, 1957; Watson, Spalding and Smith, 1962; Adams, 1970).

The tracheal pressure waveform that is produced by IPPV is only partially controlled by the ventilator itself, as the final waveform is dependent very largely upon the patient's respiratory mechanics. Also in any given situation the pressure waveform alters in shape as it is observed at different points in the airway downstream from the ventilator, and these changes in turn may vary at different flow rates. However, the tracheal flow pattern does not suffer these variations as at any given instant the flow will be the same at any two points from the ventilator output to the bifurcation of the trachea, assuming no leaks, except for very minimal changes due to gas compression and heating. Flow measurement is, therefore, a better measure of the pattern of ventilation than pressure measurement. This is especially so if the ventilator can be made powerful enough to be a flow generator (Mapleson, 1962) and so independent of patient characteristics.

A ventilator has been designed which produces a flow waveform variable over a wide range, and a block diagram of the design is shown in figure 1. The ventilator consists of a variable electronic signal generator controlling an electropneumatic interface through an amplifier. The pneumatic output is passed to the patient. A feedback circuit may be necessary if the changing load produced by the patient materially affects the output of the electropneumatic interface. Each part of the ventilator will be described with its performance where appropriate.

![Block diagram of ventilator design](image HTTPS link)

**Waveform generator.**

The waveform generator (fig. 2) which was designed and built for this purpose (Childs and Sitch, 1969) is capable of producing a widely variable electrical signal which may be displayed as a waveform. The selected signal is constructed by placing pins in a matrix board with twenty horizontal and fifty vertical steps. The "on" time of the generator has a total range of 0.05–4.99 sec in steps of 0.01 sec. During the "on" time the horizontal steps are scanned at equal time


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intervals of 1/20 of the "on" time. The "off" time is similarly controlled from 0.05 to 5.00 sec. During the "on" time the vertical position of the selector pins determines the output voltage and so wave shapes may be built up.

Electronically the waveform generator consists of a solid-state twenty-step counting ring, the counting rate of which is controlled by the "on" and "off" time oscillators. The matrix board consists of a fifty-step voltage divider, and as the counting circuit passes each column the voltage selected by the pin position is passed to a sample-and-hold and integrating circuit, which produces a fairly smooth signal output. A photograph of the electrical output of the waveform generator dictated by the pin settings in figure 2 is shown in figure 3.

The waveform generator also has the capacity for synchronous control of the solenoids in the patient inspiratory/expiratory valve. The synchronous control is arranged to prevent spill from the inspiratory to expiratory limbs and so allow accurate measurement of gas volumes. It is also possible to stop the counting ring at any predetermined point in the time cycle (either inspiratory or expiratory) with both solenoid valves closed to allow measurement of airways resistance (Neergaard and Wirz, 1927). The signal from the generator is variable up to 5 V, and a power supply of 12 V and two of 24 V are built in to the generator to supply feedback and power amplifiers, and the solenoids for the patient valve.

**FIG. 3**
Oscillographic display of the electrical signal from the pin settings of fig. 2.

**Electropneumatic interface.**

When the signal generator has produced an electrical signal of a chosen form the signal must be converted into a gas flow. This is achieved by an electropneumatic converter (Westinghouse Brake and Signal Co. Ltd) which converts the electrical signal in the first instance into a pressure which is proportional to the electrical input. If this pressure is applied to a suitable restriction the gas flow from the restriction will closely follow the shape dictated by the signal generator.

Figure 4 shows a schematic outline of the internal function of the converter. There are two chokes, or restrictions, a fixed one at A and a variable one formed by the ball-bearing F on its seat D. Movement of the ball towards the seat renders the choke A relatively less effective and the pressure rises in tube B. This causes the relay valve C to become unbalanced and so to
open and permit a flow to the outlet J. This flow will continue until the outlet pressure becomes great enough to balance the relay valve or until the ball returns to its former position. The ball is held in a cage on a spring arm and is moved by a coil in a permanent magnet assembly.

The electropneumatic converter was subjected to static and dynamic tests to judge its performance under conditions likely to be met in practice. A plot of the static pressure output against input current is shown in figure 5. It will be seen that there is a linear relationship between current and pressure when the output pressure is less than 85 per cent of the input line pressure. Thus, if the converter is supplied by 120 Lb./sq.in. and if the maximum output pressure required is less than 85 Lb./sq.in., a fall of even 20 Lb./sq.in. in the supply will not affect the output pressure. Fluctuations in input pressure are lessened by using a very stable reducing valve, and a reservoir in the input line. The supply of high pressure air to the electropneumatic converter is obtained from cylinders through a stable 120 Lb./sq.in. reducing valve (167/10B Power Dome Controller, I. V. Pressure Controllers Ltd) and is controlled by a pilot-operated spool valve immediately upstream from the converter.

The ventilator is designed to produce a predetermined gas flow waveform and it must be established that the dynamic conditions of gas flow encountered in practice do not influence the capability of any part of the ventilator. The ability of the electropneumatic converter to maintain a steady output pressure for a given current, when there is a gas flow, was tested by gradually increasing the outlet flow by means of a needle valve and measuring this flow with a pneumotachograph calibrated against an accurate Rotameter which in turn had been calibrated against a Tissot spirometer. The results are shown in figure 6 which illustrates the fall-off in pressure as the flow rate increases. The converter was further tested by connecting the output to an 80 cm³ reservoir and measuring the pressure changes in the reservoir with a piezo-electric transducer (Kistler 7031 SN 29846). The frequency response of the electropneumatic converter to a sine-wave input allowed complete reproduction to 2.5 Hz and a "flat" response (at
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the 3 db level) to 6.5 Hz. The phase delay with this frequency testing was linear to 6 Hz, demonstrating that no deformation of the waveform pattern would occur to at least 6 Hz. These values are adequate for the complete reproduction of respiratory patterns of gas flow.

Dynamic output pressure response of the electro-pneumatic converter at various fixed current inputs when the flow output is gradually increased. Three choke responses derived from fig. 7 are superimposed to show the outlet flows to be expected in use.

To convert the pressure output of the converter to a flow, the output is led directly to one of a number of chokes. The flow/pressure characteristics of these chokes are shown in figure 7 and at pressures above 10 Lb./sq.in. the relationship of flow to pressure is linear. These chokes are pieces of brass rod 1.5 cm long drilled to a size shown in table I, and threaded to fit a connector.

The overall performance of the collected pieces of interface equipment was tested by arranging the pins in the matrix board of the signal generator to give step changes in the electrical signal, and resultant flow was measured using the calibrated pneumotachograph. Figure 8 shows the correlation between pin position and flow. It follows that changes in the selected waveform will result in proportional changes in the flow produced from the choke, and so variable flow patterns may be produced. The duration of gas flow is determined by the “on” setting of the signal generator and the whole system acts as an integrator of flow against time to give a “tidal volume”. This tidal volume may be changed by adjusting the gain of the power amplifier. Because of the linearity of this system, the integral of the signal to the electropneumatic converter is directly proportional to tidal volume and thus the volume may be adjusted in a controlled manner. The potential driving pressure is so high (85 Lb./sq.in.) that back pressure of
Total dynamic output flow response of the ventilator compared to pin position on the matrix board. This shows the linearity of the ventilator response for a given electrical signal.

up to 50 mm Hg (1 Lb./sq.in.) from a patient with severe respiratory disease will produce an average of only 4 per cent fall in selected driving pressure (fig. 5). There is, therefore, no need for a feedback circuit to be used in this ventilator.

Patient valve.

The ventilator can be used with non-rebreathing valves of the Mitchell type (Mitchell and Epstein, 1966) but, to enable measurements of gas volumes and composition to be made, a solenoid-operated inspiratory/expiratory valve has been constructed (Baker and Murray Wilson, 1971). This has a resistance of 4 cm H₂O at 2 l./sec, and is designed to prevent passage of gas between inspiratory and expiratory limbs except through the patient. The solenoids are synchronously controlled by the waveform generator.

Safety device.

In the system described, the very high driving pressure necessary to operate the electropneumatic converter is separated from the patient only by a choke. If the waveform generator failed to cycle the solenoid-operated inspiratory/expiratory valve it would be possible for the patient's airways to be exposed to the driving pressure, and to exclude this hazard a safety device has been developed (fig. 9). The device consists of two fluidic Schmitt triggers (Dummer and Robertson, 1968) which drive an or/nor gate. The bias pressure of the triggers is selected to equal the greatest permissible pressure in the airways and is provided by an electric compressor working through a low-pressure regulator.

Block diagram of fluidic safety device demonstrating how either of two fluidic Schmitt triggers may be activated by airways pressure rising above a certain predetermined safety pressure. The trigger then operates a fluidic or/nor gate which itself controls a high-pressure spool valve which immediately shuts off the supply gas.

The output from the or/nor gate switches the spool valve which controls gas entry to the electropneumatic converter. It should be emphasized that if the gas pressure providing the bias fails the system is so balanced that the spool valve will drop to the safe position.

The safety device is very sensitive and has a rapid response. Complete occlusion of the breathing tube at a flow rate of 2 l./sec causes shutdown with reduction of pressure in 125 msec. This means that at this flow rate a maximum of 250 ml of gas could be injected following the generation of the set pressure. As an additional precaution a mechanical safety valve of the McKesson type is added in series between the patient valve and the patient.

Ventilator performance.

The ventilator (outline diagram shown in figure 10) has been tested against an artificial lung system with a compliance of 100 ml/cm
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H₂O and a variable resistance. Examples of flow and pressure tracings are compared with the original electrical signals in figures 11 and 12, and flow waveform closely follows the electrical signal even under load conditions. The driving gas in this ventilator is also the gas supplied to the patient. However, the system is capable of being purged of air so that anaesthetic gas mixtures may be used, including volatile anaesthetic agents if vaporizers are used that are built for operation with high-pressure gases (Bracken, Brooks and Goldman, 1968). The machine may also be used to drive a bag-in-bottle ventilating system, but this adds a capacitance which can influence the wave produced.

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REFERENCES


### UN VENTILATEUR A FORME D'ONDE VARIABLE

**SOMMAIRE**

Les auteurs décrivent un ventilateur pour patient, qui est en fait un générateur de flux gazeux en forme d'onde variable. Ce ventilateur produit un grand nombre de formes d'ondes sélectionnées de flux inspiratoire, contrôle efficacement le temps inspiration/expiration, et change le volume délivré sans altérer la forme d'onde du flux ou le temps inspiration/expiration.

### EIN VARIABLER WELLENFORM-RESPIRATOR

**ZUSAMMENFASSUNG**

Beschrieben wird ein klinischer Respirator, der einen verstellbaren und wellenförmigen Gasstrom erzeugt. Dieser Respirator ist in der Lage, eine Vielzahl von wählbaren wellenförmigen Inspirationströmen hervorzubringen, er kann darüberhinaus sehr genau die Inspirations/Expirations-Zeit kontrollieren und das abgegebene Volumen verändern bei gleichzeitiger Konstanterhaltung des wellenförmigen Gasflusses oder der zeitlichen Inspirations/Expirations-einstellung.

### UN VENTILADOR DE ONDAS DE FORMA VARIABLE

**RESUMEN**

Es descrito un ventilador para pacientes que constituye un generador de flujo gaseoso de ondas de forma variable. Este ventilador produce un gran número de formas de onda de flujo inspiratorio seleccionado, controla con exactitud el tiempo inspiratorio/expiratorio y cambia el volumen suministrado sin cambiar la forma de ondas del flujo ni el tiempo inspiratorio/expiratorio.