Fluidic technology

A discussion and a description of a fluidic controlled ventilator for use with high flow oxygen techniques

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In 1967¹ Sanders used intermittent high flows of oxygen down a bronchoscope at high pressure (50 psi*) for ventilation during bronchoscopy under general anaesthesia. The technique has been used subsequently for percutaneous transtracheal resuscitation,² for percutaneous transtracheal ventilation during general anaesthesia,³–⁵ and for general anaesthesia for laryngoscopy.⁶–¹⁰

One of the dangers of high pressure ventilation techniques is accidental high airway pressure, particularly with percutaneous transtracheal or translaryngeal ventilation, since the pressures used vary from 15 to 80 psi.

This may be due to obstruction of the upper airway either by disease or by approximation of the vocal cords under light anaesthesia.

Simple control devices have been used for these techniques. Jacobs² used a simple stopcock, Spoerel used a Bird Mark II ventilator,³ and others used a commercial hand-operated relief valve set.⁴,⁵ The fluidic ventilator described in this paper was specifically designed to increase the safety and reliability of intermittent high flow ventilation techniques. Continuous monitoring of the airway pressure (through a second catheter in the airway or a double lumen catheter) enables automatic cut-off at any preset intratracheal or intrabronchial pressure.

Fluidic technology

Fluidics is defined as that technology which utilises the phenomena of liquid or gas flow within components and circuits to perform various control functions. It is based on fluid amplifiers, most of which operate on the principle of the Coanda effect which was described more than 30 years ago. This principle, in its simplest form, states that a jet of fluid flowing from a nozzle tends to become attached to the surface of the wall adjacent to it unless deflected laterally by a force applied from the side.

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*1 psi = 6.894 kPa.

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Monostable amplifier

Fig. 1 shows how a fluid amplifier operates. The air flows from the power source (P,) into the amplifier where it goes to the nozzle. The orifice of the nozzle opens into two outlets, O, and O₂. The jet stream which flows from the nozzle becomes attached to the wall of one orifice because it creates an area of low pressure in the corner of the outlet. The flow remains in this particular outlet for as long as there is equilibrium between the pressures applied to the control ports (C) and the vent. If a control signal pressure is applied at the control port C, it deflects the fluid jet from the outlet O₂ to the outlet O₁. The fluid jet returns to the original outlet after control pressure is discontinued; hence the name 'monostable' because the amplifier has only one stable position in the absence of control signals.

The term amplifier is used because the control pressure is a fraction of the pressure of the main jet and is amplified to the dimensions of the fluid jet. In effect it is really the fluidic equivalent of an electronic diode.

Bistable amplifier (flip-flop)

In the 'flip-flop' amplifier (Fig. 2) the fluid jet operates similarly but does not return to the original outlet after the control pressure is discontinued. It is also called a memory amplifier because, in effect, it 'memorises' the control signal that was received last. The amplifier has two stable positions of the outflow jet, O₂ or O₁, and is, therefore, called bistable or flip-flop.

Decision-making gates (monostable amplifiers)

Fig. 3 shows schematic diagrams of several monostable amplifiers, also called decision-making gates or logic amplifiers. The fluid jet normally passes from the power source, P,, into the output O₂. When there is a control signal applied on the control inputs, C₁, C₃, C₅ or C₇, the jet is deflected into the output O₁. The output is held at O₁ as long as sufficient pressure remains at any of the control inputs C₁, C₃, C₅ or C₇. When there is no control signal on any of these control ports, the output immediately returns to its stable state at O₂. This type of fluid amplifier is called OR/NOR because there are two choices OR or NOR (NOR = NOT OR and is the logical negation of OR).

The second type of monostable amplifier is the AND/NAND (NOT AND) when both control signals C₁ and C₃ are present. If no control signal, or only one of them is
present, the output remains at \( O_2 \). This gate provides the logic AND function, and its complement NAND.

Finally, another type of monostable amplifier is the INHIBITED OR amplifier. It operates similarly to the OR/NOR amplifier except that the transfer of the output from \( O_2 \) to \( O_1 \) may be inhibited by applying control pressure at the control port \( C_2 \). The control pressure at \( C_2 \) overrides the normal effect of the control pressures at \( C_1 \) or \( C_3 \). This means that it inhibits the effect of \( C_1 \) and \( C_3 \) controls.

As logic components, monostable amplifiers are called decision-making gates because the amplifier is constructed so as to decide when a desired combination occurs, and act on this decision by switching its output.

**Memory amplifiers (bistable amplifiers)**

The other group, called 'memory amplifiers', is shown in Fig. 4. In the basic flip-flop amplifier, the main jet is randomly attached to one output when the power source is switched on. When a control signal is applied on the side of this output, the jet switches to the opposite output where it remains and no other signal is applied. The preferred flip-flop is constructed so that it always starts in one output (\( O_1 \) in this case) and does not switch on randomly to the other output.
The binary counter counts by using the two-digit binary numbering system as in electronic circuits. In the binary system, the only digits used are 0 and 1. This component can accept a series of signals at its count inputs, \( C_3 \) and \( C_4 \), and switches its complementary binary outputs, \( O_1 \) and \( O_2 \), alternately on and off in response to each pair of input signals. The counter also has a set and reset input \( C_2 \) and \( C_1 \), and it has outputs \( O_3 \) and \( O_4 \) for staging connections between several counters.

**Medical application of fluid amplifiers**

*Simple ventilator*[^11]

This can be constructed as shown in Fig. 5 by having a side arm attached to the output of a monostable amplifier and connected as a feedback to the control input \( C_1 \). When a fluid jet reaches the output, it passes simultaneously into the side arm and through the feedback line to the control input where it switches the jet from the inspiratory to the expiratory outlet. The feedback signal can be delayed by a regulator or a needle valve and this regulates the duration of the jet at the outlet. If this outlet is connected to a patient's airway by means of an endotracheal tube or a mask, the amplifier functions as a simple ventilator.

![Fig. 5. A simple fluidic ventilator.](image)

**Blood pump**[^12]

Fig. 6 shows a fluid amplifier-driven blood pump where the principle is similar to the ventilator. The jet switching from one outlet to another and back compresses the blood sac and produces systole and diastole of the pump controlled by the feedback control system. The entrance port in the air chamber provides the control signal for switching to diastole after it is opened by completely compressing the blood sac, and the control port open to the atmosphere from the opposite direction provides the feedback for switching to the systolic mode again.

Fluidic technology provides many possible advantages for control systems which include the absence of moving parts (low maintenance, high reliability) and immunity...
from environmental changes (extremes of temperature, electronic 'noise', high humidity, radiation, vibration and there is no explosion hazard). Several lateral fluid amplifiers can also be connected (staged) together to provide increased amplification at each consecutive stage, or connected into a network to perform complex tasks.

The high power consumption and relatively slow response time (in milliseconds) compared to electronic systems (in nanoseconds) are disadvantages, but the response time is adequate for biomedical applications. When an amplifier operates it uses up the same amount of energy (flow) in expiration as in inspiration despite the fact that it operates during inspiration only, and all the other flow is wasted. Its efficiency is therefore about 30%.

Fig. 6. A fluidic blood pump.

Fig. 7. A fluidic controlled ventilator. A = pressure regulator and connector; B = power interface valve; C = jet injection cannula; D = sensing line; E = low pressure regulator; F and G = regulators; H = indicator light; I = dial; J = control assembly.
A fluidic controlled ventilator

Fluid amplifiers are utilised only for control purposes to interrupt the operational 50 psi pressure by operating a power interface valve. It is a 'second generation' of medical fluidic devices. The basic components came from the 'Corning Basic Medical Fluidikit'.

The device (Fig. 7) consists of a high pressure connector with pressure regulator (A), which can be plugged into any oxygen outlet in the operating room or in the wards. This regulator is used to maintain the pressure of the jet which will be used for ventilation (30–50 psi). The high pressure oxygen goes through a high pressure line to the power interface valve (B), which interrupts the flow from the supply line to the jet injection cannula (C). The power valve is controlled by a low pressure signal of 3 psi* from the control assembly J. This module consists of four fluid amplifiers mounted on a basic board and contains the regulators F and G which determine the durations of inspiration and expiration. The upper box supplies the low pressure to the control system and has its own regulator E, indicator light H, and dial I, to monitor the pressure in the sensing line D. This sensing line can be placed close to the injection catheter in the airway and provides the feedback for a cut-off of high-flow ventilation at about 20–30 cmH2O. The efficiency is better than that of other devices because the high-pressure high-flow jet is open only during the active inspiration.

The control module consists of four fluid amplifiers, the main one being the flip-flop. Two time-delay relays with regulators provide for adjustment of duration of inspiration and expiration. The fourth amplifier is for the cut-off sensor.

The operation of the device can be described as follows (Fig. 8): the output of the main amplifier (in the middle) alternates between O2 and O1 (output) in relation to the adjustment of time-delay relays (TDR) 1 and 2. Closing the regulator (2) progressively delays the feedback signal from O1 output to the C4 control port in the amplifier. When the signal reaches the amplifier, it switches the jet from O1 to O2, and the other time-delay relay and its regulator (1) controls the duration that the jet will remain in the O2 output. The O1 output represents expiration and is indicated by a fluidic light; O2 represents inspiration. The jet from the O2 output goes not only to the TDR, but also provides the signal to the interface valve which will open and remain open as

* 1 psi = 6.894 kPa
long as the jet remains in the O₂ output. During this inspiratory period, the main jet of 50 psi pressure goes via the ventilation catheter to the patient.

The sensing tube which is placed in the airway of the patient is connected to the fourth amplifier at the control port C₁. This is a differential amplifier which has reference control input C₂ on the opposite side. The more the regulator (3) is open, the higher the pressure at the C₂ control port; thus a higher pressure is needed at the C₁ entrance (connected to the sensing tube) to switch the output of this amplifier from O₂ to O₁. The pressure is monitored on a manometer. When it increases above the preadjusted level, the output of the amplifier switches from O₂ to O₁. The O₁ then provides the control signal to the control port at C₁ of the main amplifier. When the control signal C₁ reaches this amplifier, it switches the output of this jet from O₂ to O₁ and terminates the duration of inspiration. This causes the interface valve to close immediately.

Mechanically, the entire device is assembled in a compact enclosure and is very easy to operate because there are only three knobs to adjust (Fig. 9). One regulator determines the duration of inspiration (Inspiratory Time), another regulates the rate by altering the expiratory time, and a third can be used to adjust the cut-off pressure. The fourth knob marked 'Fluidic oxygen supply' is the main supply regulator for the control module and is locked in place after an initial adjustment to suit the line pressure at any individual institution, and does not need to be changed except in the unlikely event of variation in pipeline pressure.

Summary

The principles of fluidic technology are outlined and applied in the description of a fluidic controlled ventilator. The device is compact, easy to operate and practically
fail-safe since it has no moving parts. There is a sensor which prevents any increase in airway pressure above the preset level.

References