APPARATUS

The ‘fixed performance’ venturi: effect of downstream pressure on outflow and $F_{1O_2}$

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Summary

Fixed performance venturi devices should provide a predetermined oxygen concentration at an outflow which exceeds an adult’s peak resting inspiratory flow rate (approximately 30 l.min$^{-1}$). Campbell’s original description mentioned the sensitivity of the venturi device to downstream resistance but gave no further details. This study examined outflow and oxygen concentration from the five standard venturi devices (24–60% O$_2$) when downstream pressure increased. Outflow was exquisitely sensitive to small increases in pressure. The outflow at zero downstream pressure for the 24–40% O$_2$ venturi devices ranged from 40 to 50 l.min$^{-1}$ but only 2–3 mmH$_2$O was needed to halve this flow and increase oxygen concentration. The 60% O$_2$ venturi delivered a maximum of only 30 l.min$^{-1}$ at zero downstream pressure and flow was reduced further by increasing this pressure. An increase in downstream pressure of only a few mmH$_2$O increased oxygen concentration and decreased outflow of all the venturi devices tested, in most to less than normal peak tidal flow in adults.

Keywords Oxygen inhaled therapy; inspiratory flow, Ventimask, venturi.
effects of varying downstream resistance on venturi performance to see if this could explain the insufficient gas delivery previously described [11, 12].

Methods
A set of standard venturi devices was studied (Flexicare Medical Ltd, Mountain Ash, Mid Glamorgan, UK). These were claimed to deliver an output of 24, 28, 35, 40 and 60% oxygen when a pure oxygen supply of 2, 4, 8, 10 or 15 l.min$^{-1}$ was connected. The outflow (l.min$^{-1}$), calculated from the delivered oxygen concentration, was compared with directly measured values using a Wright’s respirometer and Fleisch No. 1 and No. 4 pneumotachographs (A. Fleisch, Lausanne, Switzerland). The pneumotachographs were connected to a Validyne transducer (Validyne Engineering Sales Corp., Northridge, CA) model SN7342 (pressure range ± 20 mmH$_2$O) and a purpose built amplifier [13]. The respirometer and pneumotachographs were calibrated using a standard 20 l.min$^{-1}$ rotameter (Rotameter Manufacturing Co., Nachiket Business Centre, Mumbai, India; Tube no. 287291/1005/51). The Fleisch No. 1 (Number 1967) pneumotachograph supposedly generates a pressure drop of 2.2 mmH$_2$O at 20 l.min$^{-1}$ (manufacturer’s calibration) but the actual pressure drop was 2.5–3 mmH$_2$O at 20 l.min$^{-1}$. The pressure drop across the Wright’s respirometer was 1.5 mmH$_2$O at 20 l.min$^{-1}$. To reduce this downstream pressure the No. 4 (Number 1090) Fleisch pneumotachograph was used. This had a cross-sectional area of 26 cm$^2$ (compared to 2.5 cm$^2$ for the No. 1 instrument) and a calibrated pressure drop of 0.2 mmH$_2$O at 20 l.min$^{-1}$ and 10 mmH$_2$O at 14.19 l.s$^{-1}$. The flow signal was transferred by a PICO ADC-11 data acquisition system (PICO Technology Ltd, Cambridge, UK) for analysis and display on a personal computer. Pressure changes were measured with a water manometer and a steel rule scale engraved in 0.5-mm divisions. Oxygen was measured with an Ohmeda 4700 Oxycap (Datex-Ohmeda Ltd, Hatfield, UK) calibrated with a certified gas mixture supplied by the manufacturers. A medical oxygen gas cylinder (British Pharmacopoeia; Medigas, http://www.praxair.com/healthcare) was purchased from a local pharmacy.

To examine the effect of increasing downstream pressure on venturi performance, a 10-cm length of 2.5-cm internal diameter rubber tubing was inserted between the venturi and the input cone of the Fleisch No. 4 pneumotachograph (Fig. 1). The tube was narrowed with a screw clamp. A blunt needle attached to a water manometer was inserted through the wall of this tube between the venturi and the clamp position. Using a lens, the difference between the menisci was read to the nearest 0.5-mm marking on the manometer scale.

After completing the study on the Flexicare venturis, another set of venturi devices was tested (‘Old set’, manufacturer unknown). Unlike the Flexicare products they had a shiny finish with letters stamped on in black rather than embossed and with different shaped ports. These delivered the same range of oxygen concentrations as the Flexicare devices using, respectively, the same input flow rates. Finally a set of three venturis from Profile Human Systems (Bognor Regis, UK) was examined. These gave 24% $O_2$ at 3 l.min$^{-1}$ inflow, 31% $O_2$ at 8 l.min$^{-1}$ inflow and 40% $O_2$ at 12 l.min$^{-1}$.

Theory
For the required oxygen concentration to be delivered to the patient, the flow rate from the venturi must exceed tidal flow. In normal adults, tidal flow peaks at about
A normal flow pattern is shown in Fig. 2 with a hypothetical venturi flow rate shown at 32 l.min\(^{-1}\). In this case the excess oxygen mixture blows out through the holes in the mask during inspiration. If the venturi flow is only 16 l.min\(^{-1}\) then tidal flow exceeds venturi flow for part of the breath and air is drawn through the holes in the mask and dilutes the inspired oxygen concentration.

Venturis work by directing a high velocity gas jet into an expanded tube. Depending on the design of the tube, the resulting pressure (Bernoulli effect) drops below atmospheric and air is drawn through the large holes in the venturi wall (Fig. 3). Further downstream, as the high velocity jet is dissipated, the pressure recovers to a few mmH\(_2\)O above atmospheric. The relationships between the fresh gas flow from the rotameter, the entrained atmospheric air and resultant \(F_{I\text{O}_2}\) and flow output are shown in Fig. 3.

### Results
Flow output delivered by each of the five Flexicare venturis was first measured using a Wright’s respirometer. For comparison the output flow was calculated for each venturi using the relationship in eqn. 2 shown in Fig. 3 for each type of venturi. The predicted and measured outflow values (Wright’s) are shown in Table 1 for the five venturis. A large discrepancy was found between these two values. Because of the lower than expected flow seen with the Wright’s respirometer, further experiments were carried out with a Fleisch No. 1 pneumotachograph. There was a further reduction in outflow with each venturi device (Table 1). It was deduced that the lower than expected outflow was a function of the resistance of the measuring device itself and to overcome this the much larger Fleisch No. 4 pneumotachograph was used to show that the measured and calculated flows were identical (Table 1).

A series of experiments was carried out with each of the five Flexicare venturis where the downstream resistance was increased in a stepwise fashion and the flow output and oxygen concentration were recorded. Figure 4 shows the linear fall in outflow with increasing downstream pressure. Only 2–3 mmH\(_2\)O was needed to reduce flow by 50% in the 24–40% O\(_2\) venturis. The 60% O\(_2\) venturi was much less susceptible to this effect. Outflow ceased between 5 and 6 mmH\(_2\)O for the 24–40% venturis but > 15 mmH\(_2\)O was required to stop flow from the 60% O\(_2\) venturi.

The effect of the reduction in flow on the oxygen output concentration was calculated and measured experimentally (Fig. 5). These results were similar at high flows; the calculated curves reached 100% oxygen at the input flow rate of the venturi, whereas the experimental data differ from the theoretical at low flows.

### Table 1
Comparison of predicted and measured outflow for the five Flexicare venturis. All values are l.min\(^{-1}\).

<table>
<thead>
<tr>
<th>Venturi Type</th>
<th>24</th>
<th>28</th>
<th>35</th>
<th>40</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted (V_{OUT})</td>
<td>Model 53</td>
<td>45</td>
<td>45</td>
<td>42</td>
<td>30</td>
</tr>
<tr>
<td>Measured (V_{OUT})</td>
<td>Wright’s respirometer</td>
<td>40</td>
<td>32</td>
<td>31</td>
<td>28</td>
</tr>
<tr>
<td>Measured (V_{OUT})</td>
<td>No. 1 Pneumotachograph</td>
<td>31</td>
<td>22</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>Measured (V_{OUT})</td>
<td>No. 4 Pneumotachograph</td>
<td>53</td>
<td>45</td>
<td>44</td>
<td>39</td>
</tr>
</tbody>
</table>

\(V_{IN}\), inflow to venturi. \(V_{OUT}\), outflow from venturi.
The effect of different devices attached to the outlet of a 40% venturi device are shown in Table 2. Note the considerable rise in oxygen concentration when a Wright’s respirometer and, particularly, a No. 1 pneumotachograph are added downstream. The latter result is consistent with the output of 28 and 16 l.min$^{-1}$, respectively, shown in Table 1 and the calculated oxygen concentrations were 49 and 70%, respectively.

After completing the study on the Flexicare venturis, the ‘Old set’ (manufacturer unknown) of venturi devices were tested. The results of the flow pressure studies were similar to those described above, although there were higher flows, the 24% venturi delivering up to 70 l.min$^{-1}$ (Fig. 6). The three venturis from Profile Human Systems had a polished finish similar to the ‘Old set’ but the external dimensions were smaller and the diameter of the venturi jet in each case was larger than either the Flexicare or the ‘Old set’ devices. The results with the Profile Human Systems venturis showed slightly lower flows than those seen in the Flexicare venturis in Fig. 6.

**Table 2** Effect of various devices on oxygen output concentration (%).

<table>
<thead>
<tr>
<th>Device</th>
<th>Oxygen concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40% venturi + 5.5 × 1.9 cm connector</td>
<td>40</td>
</tr>
<tr>
<td>Plus Wright’s respirometer</td>
<td>51</td>
</tr>
<tr>
<td>Plus Fleisch No. 1</td>
<td>75</td>
</tr>
<tr>
<td>Plus Fleisch No. 4</td>
<td>40</td>
</tr>
<tr>
<td>117 cm × 2.1 cm diameter corrugated tube-straight</td>
<td>41</td>
</tr>
<tr>
<td>Same corrugated tube in a U-bend</td>
<td>42</td>
</tr>
<tr>
<td>Adult MC mask with holes occluded</td>
<td>43</td>
</tr>
</tbody>
</table>

**Figure 4** The relationship between outflow and downstream pressure for five Flexicare venturis. Note that the 24–40% O$_2$ venturi devices give a much higher outflow than the 60% O$_2$ venturi, the latter being less susceptible to pressure. ■ 24, □ 28, ▲ 35, ○ 40, △ 60% O$_2$ devices.

**Figure 5** Comparison of the predicted relationship between outflow and oxygen concentration (continuous lines) and the measured relationship (symbols) in the five Flexicare venturis. Note that the predicted values intersect the horizontal axis at the driving flow rate (2, 4, 8, 10 and 15 l.min$^{-1}$). ■ 24, □ 28, ▲ 35, ○ 40, △ 60% O$_2$ devices.

**Figure 6** The relationship between pressure and outflow for the ‘Old set’ venturis (manufacturer unknown). Compare with Figure 4. ■ 24, □ 28, ▲ 35, ○ 40, △ 60% O$_2$ devices.
Discussion

The Wright’s respirometer and Fleisch No. 1 pneumotachograph that were used to measure flow output from the venturis were themselves adding a downstream resistance which reduced flows to considerably less than the calculated (ideal) values. This demonstrated that venturi outflow is exquisitely sensitive to downstream pressure. For the 24–40% O₂ Flexicare venturis, only 2–3 mmH₂O was needed to produce a 50% fall in flow but three times this pressure was needed to halve flow from the 60% O₂ venturi. This susceptibility to pressure is due to the design of the venturi, with only a very small positive pressure (pressure recovery) downstream of the jet. The large holes in the venturi sidewall downstream of the jet efflux are designed for air entrainment and this allows ready egress of the oxygen air mixture if downstream pressure rises by a few mmH₂O.

Despite the assertion that the Ventimask is a fixed performance device, there has long been uncertainty whether it invariably provides sufficient flow to maintain the required F(IO₂) throughout inspiration. While venturi devices are commonly used in clinical practice, few users know that the outflow rate is more than 40 L.min⁻¹ for the 24–40% O₂ devices, although this is easy to calculate using eqn. 2 in Fig. 3 if the oxygen concentration is measured. Campbell [9] proposed the use of a lighted cigarette held near the large holes in the mask to show, if the cigarette glows with increased brightness or even bursts into flame, that excess oxygen was leaking out throughout the respiratory cycle. In contrast, he suggested that if the patient coughed, cigarette smoke, a tracer for room air, was being entrained through the mask.

In the present study the predicted and measured outflows using the large, No. 4 Fleisch pneumotachograph (Table 1) were identical for all five Flexicare venturi devices and for most exceeded 40 L.min⁻¹. The outflow with the 60% O₂ venturi, 30 L.min⁻¹, was the lowest and because this is close to normal peak tidal flow, explains the susceptibility to entrain more air if ventilation increases. The 60% O₂ venturi was the least sensitive to an increase in downstream pressure and the 24–40% O₂ devices showed a greater sensitivity. The differences in sensitivity between the latter two devices were small (Fig. 4).

The reduction in flow produces a progressive rise in downstream oxygen concentration (Fig. 5). In each venturi the theoretical outflow line reaches 100% oxygen as inflow equals outflow, which is at 2, 4, 8, 10 and 15 L.min⁻¹, respectively. When this relationship was compared with experimentally derived data points they were essentially similar at high flows but below a flow of about 10–15 L.min⁻¹ the theoretical and experimental relationships diverged.

Jones et al. [11] in a complex experiment using an artificial head showed that the 60% O₂ mask was most sensitive to increased breathing in normal subjects delivering 45% rather than 60% oxygen. They did not measure venturi output and attributed the fall in F(IO₂) to a dilution effect due to rebreathing of mask dead space. Woolner & Larkin [12] studied the Hudson multivent mask and actually measured the venturi output with a Fleisch No. 2 pneumotachograph and Validyne transducer similar to those in the present study. The pressure drop across this pneumotachograph was equivalent to 1 mmH₂O at 20 L.min⁻¹. This was less than one third of the pressure drop in the Fleisch No. 1 at the same flow, and showed that the oxygen delivery was sensitive to patients’ peak tidal flow, the F(IO₂) falls when inspiratory flow rate exceeds 40 L.min⁻¹.

After completing the study on the Flexicare venturis, another set of venturi devices was tested ('Old set'). The results of the flow pressure studies on these devices were similar to those described above, although there were higher flows, the 24% O₂ venturi delivering up to 70 L.min⁻¹ (Fig. 6). Compared with the results in Fig. 4 the flows were generally greater, although the effect of downstream pressure was similar. The three venturis from Profile Human Systems had smaller external dimensions than the ‘Old set’ but the diameter of the venturi jet in each case was larger than that of either the Flexicare or the ‘Old set’ venturi. As expected, the Profile Human Systems devices gave slightly lower flows than those seen in the Flexicare venturis shown in Fig. 4.

There are probably many different venturi devices available with slightly different outflows and susceptibilities to downstream pressure. The simplest check on their performance is to use a gas analyser to measure the delivered oxygen concentration and equation 2 to calculate outflow.

Acknowledgements

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References


