An Analysis of the Performance of a Variable Venturi-type Oxygen Mask

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SUMMARY
The theoretical performance of the Hudson Multivent mask is considered. A method is described of determining the flow-weighted mean inspired oxygen concentration produced by the mask. Using this method, it was found that the inspired oxygen concentration was predictable only at the 24% setting using the recommended flow rates, but that increasing the supplied-oxygen flow rates above the recommended levels resulted in the return of predictable function. At settings above 30% predictable function was found to be unlikely, whatever the supplied oxygen flow rate. Recommendations are made regarding the use of this device.

INTRODUCTION
Many devices are available to increase the concentration of inspired oxygen. They have been classified by Leigh1,2 into those exhibiting fixed performance, and those exhibiting variable performance. Fixed performance devices deliver fresh gas at rates in excess of the peak inspiratory flow rate (PIFR) of the recipient. At all stages of inspiration, therefore, the inspired gas is supplied by the mask, and the inspired oxygen concentration is fixed and predictable.

Variable performance devices deliver fresh gas at a rate which may be exceeded by the PIFR. The PIFR varies between individuals, and between breaths in the same individual. Room air is therefore entrained into the mask at a variable rate, and the final inspired oxygen concentration is unpredictable and inconstant.

Venturi-type masks were found by Leigh to exhibit fixed performance. Since these reports,1,2 several variable Venturi-type masks have become available. One such device is the Hudson Multivent Mask.

THEORETICAL CONSIDERATIONS
Venturi-type masks operate by supplying 100% oxygen through a nozzle, with the controlled entrainment of room air through ports in the barrel. The admixture of these two gas sources results in a total fresh gas flow containing a set percentage of oxygen. To produce a set final oxygen concentration from a given 100% oxygen flow rate, a predictable amount of room air must be entrained into the barrel of the mask. The total gas flow rate may therefore be predicted arithmetically from the formula:

\[
\text{Total gas flow} = \frac{Y (100-C) + Y}{C-21}
\]

where \( Y \) = supplied (100%) oxygen flow rate
\( C \) = final (set) oxygen concentration
\( 21 \) = oxygen content of room air

Figure 1 shows the total gas delivery rate, calculated from this formula, for each setting of the Multivent mask with increasing 100% oxygen flow rates.

For a PIFR of 30-50 l/minute, at the recommended oxygen flow rates, the mask may be expected to exhibit fixed performance at low concentration settings, and variable performance at high concentration settings.

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**Figure 1.**—Relationship between total gas delivery rate and supplied-oxygen flow rate for each setting of the Multivent mask.

**Figure 2.**—Diagrammatic representation of the apparatus used.
MATERIALS AND METHODS
This study was designed to show that, with the Hudson Multivent mask, variation in performance does occur. Further, the range of settings over which fixed performance could be restored by increasing the supplied-oxygen flow rate was evaluated.

The measurement of oxygen concentration in the upper airway presents certain difficulties, such as the passage of sputum or saliva into the sampling apparatus. The measurement of gas flow rate from this site is also technically difficult. In order to facilitate these measurements a "false face" was constructed.

This consisted of an interface, through which a perspex tube, 3 cm long and 3 cm in diameter, was inserted (Figure 2). A Luer connector allowed the insertion of the probe from a Perkin Elmer M.G.A. 1100 mass spectrometer into the tube lumen at a point 1 cm from the aperture. The dead space from the point of inspiration to the probe was 7 ml. The mass spectrometer was calibrated for oxygen measurement using room air and 100% oxygen.

A Fleisch No. 2 pneumotachograph was inserted into the end of the tube distal to the mask, and connected to a Validyne M.P.45 transducer containing a diaphragm linear in response up to 2 cm of water pressure.

1 cm of water pressure was equivalent to a flow, through the pneumotachograph, of 3.362 l/sec. Thus the apparatus was suitable for measurement of flow rates from zero up to 405.4 l/min. The pneumotachograph was calibrated for inspiratory flow using a Collins rotameter-type flow meter.

The outputs of both the mass spectrometer and the pneumotachograph were fed into a P.D.P.11/10 computer, fitted with a Tektronic IX 4012 graphics terminal, and hard print-out facility. The computer was programmed to allow the following:

1. The logging of instantaneous oxygen concentrations, and inspiratory flow rates at a rate of 8 cycles/sec.
2. Instantaneous and simultaneous display, in graphic form, of oxygen concentration and inspiratory flow rate with respect to time.
3. The availability of stored data for further manipulation.

A further program was developed to calculate the flow-weighted mean oxygen concentration (FwMO₂) for a total period of one inspiration, according to the formula:

\[
FwMO₂ = \frac{\int (O₂ \text{ concentration} \times \text{inspiratory flow rate}) \text{dt}}{\int \text{inspiratory flow rate. dt}}
\]

where t = time.

There was a lag of 0.25 seconds of the oxygen concentration signal, behind that of the pneumotachograph. This represented the time taken for gas to pass from the probe to the mass spectrometer. A correction was applied for this artifact.

Two indices of fixed performance were used. Firstly, as the mask does produce the expected oxygen concentration in the final gas mixture at all settings of the mask, and at all supplied-oxygen flow rates tested, a fall in FwMO₂ below specified levels represents the onset of variability. Secondly, when the mask is behaving in a fixed manner, the tracing of inspired oxygen concentration should rise rapidly at the beginning of inspiration to a plateau equal in value to the setting on the mask. This plateau should be evenly sustained during the inspiration, and throughout dead space elimination in early expiration. A break-up of this plateau phase, together with a failure to reach expected levels, also indicates variable performance. Figure 3 shows typical fixed and variable tracings.

![Figure 3. Tracings showing typical fixed and variable characteristics.](image-url)

(a) 26% oxygen setting of the mask, with 6 l/minute supplied-oxygen flow rate. Fixed performance is demonstrated by the rapid rise and smooth plateau of the oxygen trace.
without coaching, throughout. PIFR varied between 40 l/min and 60 l/min during the experiment. (Mean = 47 l/min. S.D. = 5.3 l/min.)

Experiment 1

Each of five Multivent masks were attached to the apparatus in turn, so that no significant leaks were apparent around the mask margins. At each setting of the mask (24%, 26%, 28%, 30%, 35%, 40% and 50% oxygen), the supplied-oxygen rate was adjusted to the manufacturer's recommended level. The subject (a healthy male, aged 28 years, weight 89 kg) then breathed quietly through the apparatus. The data were logged and displayed for a period of 15 secs. The Fwmo, was then calculated for each of three inspirations, and the average was taken.

The supplied-oxygen flow rate was increased incrementally and the procedure repeated.

Experiment 2

For the mask settings of 35%, 40% and 50% oxygen, the procedure was repeated with a supplied-oxygen flow rate of 10 l/min, and the PIFR was varied. The Fwmo, for each breath was calculated, and plotted against the PIFR for that breath. Thus, the change in performance of the mask with rising PIFR was documented.

RESULTS

Table 1 shows the average Fwmo; for three breaths, for each of the masks, for each of the concentration settings, together with the supplied-oxygen rate used. No effort was made to standardize the PIFR obtained during testing, the volunteer breathing quietly, but

<table>
<thead>
<tr>
<th>Mask Characteristics</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
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<tr>
<td>24% at 3 l/min</td>
<td>23.9</td>
<td>23.9</td>
<td>23.9</td>
<td>23.7</td>
<td>23.8</td>
</tr>
<tr>
<td>24% at 6 l/min</td>
<td>24.4</td>
<td>24.4</td>
<td>24.4</td>
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<td>24.2</td>
</tr>
<tr>
<td>26% at 3 l/min</td>
<td>25.4</td>
<td>25.2</td>
<td>24.8</td>
<td>24.8</td>
<td>24.7</td>
</tr>
<tr>
<td>26% at 6 l/min</td>
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<td>25.5</td>
<td>25.7</td>
<td>25.2</td>
<td>25.2</td>
</tr>
<tr>
<td>28% at 3 l/min</td>
<td>26.6</td>
<td>25.3</td>
<td>25.4</td>
<td>25.9</td>
<td>25.7</td>
</tr>
<tr>
<td>28% at 6 l/min</td>
<td>27.6</td>
<td>26.6</td>
<td>27.5</td>
<td>27.2</td>
<td>28.5</td>
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<td>28% at 9 l/min</td>
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<td>28.2</td>
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<tr>
<td>30% at 3 l/min</td>
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<td>25.4</td>
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<td>30% at 5 l/min</td>
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<td>27.5</td>
<td>27.3</td>
<td>27.6</td>
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<tr>
<td>30% at 7 l/min</td>
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</tr>
<tr>
<td>30% at 9 l/min</td>
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<td>29.9</td>
<td>28.6</td>
</tr>
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<td>35% at 6 l/min</td>
<td>31.6</td>
<td>29.1</td>
<td>29.0</td>
<td>29.0</td>
<td>29.5</td>
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<tr>
<td>35% at 8 l/min</td>
<td>32.3</td>
<td>29.5</td>
<td>30.6</td>
<td>31.0</td>
<td>30.1</td>
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<tr>
<td>35% at 10 l/min</td>
<td>33.4</td>
<td>29.5</td>
<td>31.7</td>
<td>31.0</td>
<td>29.8</td>
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<tr>
<td>35% at 12 l/min</td>
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<td>35.0</td>
<td>31.9</td>
<td>31.7</td>
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<tr>
<td>40% at 6 l/min</td>
<td>35.0</td>
<td>28.4</td>
<td>30.2</td>
<td>29.6</td>
<td>27.6</td>
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<tr>
<td>40% at 8 l/min</td>
<td>35.4</td>
<td>29.6</td>
<td>33.2</td>
<td>31.1</td>
<td>29.6</td>
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<tr>
<td>40% at 10 l/min</td>
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<td>31.2</td>
<td>34.2</td>
<td>32.3</td>
<td>32.2</td>
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<tr>
<td>40% at 12 l/min</td>
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<td>33.9</td>
<td>35.8</td>
</tr>
<tr>
<td>50% at 6 l/min</td>
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<td>29.4</td>
<td>29.9</td>
<td>31.0</td>
</tr>
<tr>
<td>50% at 8 l/min</td>
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<td>31.0</td>
<td>32.7</td>
<td>32.7</td>
<td>33.5</td>
</tr>
<tr>
<td>50% at 10 l/min</td>
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<td>33.6</td>
<td>35.2</td>
<td>34.2</td>
<td>35.6</td>
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<td>50% at 12 l/min</td>
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<td>38.2</td>
<td>38.1</td>
<td>38.8</td>
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<tr>
<td>50% at 14 l/min</td>
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<td>36.5</td>
<td>37.1</td>
<td>39.9</td>
<td>38.3</td>
</tr>
</tbody>
</table>

Figures 4, 5 and 6 show the variations of Fwmo, with PIFR for the 35%, 40% and 50% settings. The supplied-oxygen flow rate was 10 l/min in each case.

DISCUSSION

Oxygen is frequently administered in current medical practice. Usually, it is unnecessary to be precise about the inspired oxygen concentration, provided that some enrichment is occurring. Sometimes, an accurate knowledge of inspired oxygen concentration is essential. Such occasions include the management of chronic obstructive airways disease and of progressive respiratory failure.
Figure 4.—Relationship of FwMO and PIFR at the 35% setting of the mask.

Figure 5.—Relationship of FwMO and PIFR at the 40% setting of the mask.
Venturi devices are often considered to be of fixed performance. Table I indicates that this is not necessarily so, at least for the Hudson Multivent mask.

Many studies have examined the inspired oxygen concentration obtained with various devices. The sites at which sampling has occurred include the mask, the mouth, the nasopharynx, and the trachea. Assessment of PaO₂ and plots of the gas R line have also been used to assess inspired oxygen concentration. In none of these studies was the FWMO, documented.

The FWMO has considerable advantages over mean or peak inspired oxygen concentration. The calculation of mean inspired oxygen concentration gives equal weight to all instantaneous oxygen percentage measurements. It is valid only when the gas flow is constant. Gas flow during inspiration is not constant. A change in oxygen percentage occurring at a time of high gas flow will have more effect on the overall inspired oxygen than the same change occurring at a time of low flow. By calculating the total volume of inspired oxygen, and dividing this by the total volume of inspired gas, it is possible to “weight” each oxygen concentration measurement according to the flow occurring at that time. The formula used to calculate FWMO, performs this manœuvre.

The calculation of FWMO, involves the recording of simultaneous oxygen and flow measurements. In order that this may be accomplished, oxygen sampling must occur as close to the point of inspiration as possible. If sampling occurs from further down the respiratory tree, dead space effects lead to delays between the two signals. The sampling point in the “face” was 1 cm from the point of inspiration.

In previous studies, streaming of gases has been reported in the upper airways. This has been reported to produce up to 6% difference in oxygen concentration between the margin and centre of the airway. In the apparatus described, movement of the spectrometer probe across the tube diameter during the steady passage of gas through the apparatus produced no significant alteration of the oxygen signal. It is impossible to exclude streaming at some stages of the respiratory cycle, however.

The data in Table I indicate that, except for
the 24% setting, supplied-oxygen flow rates in excess of those suggested by the manufacturer must be used to produce a FwMO₂ of the expected value. On the settings above 30%, even the increased supplied-oxygen flow rates tested failed to produce the expected FwMO₂, and the mask continued to behave in a variable manner. Scrutiny of the tracings obtained during the experiments confirmed this observation.

Reference to the total gas flows predicted at each setting shows that this figure must exceed PIFR by some 30% before fixed performance can be assumed.

Only five masks were tested. Only limited conclusions can be drawn, therefore, regarding uniformity of function between individual masks. At high percentage settings the variable nature of the mask function precludes comparison of one mask with another. At low settings there appears to be reasonable uniformity between the masks tested.

Figures 4, 5 and 6 show the relationship between PIFR and FwMO₂ at settings of the mask above 30% oxygen. At low PIFR the FwMO₂ forms a plateau around the expected value. As PIFR rises a sharp fall-off in FwMO₂ occurs. At the 35% setting this decline occurs at 40-50 l/min. At the 40% setting it occurs at 30-40 l/min and, at the 50% setting, at 20-30 l/min. In all these cases the supplied-oxygen flow rate was above that recommended by the manufacturer. Had a flow of 6 l/min been used the decline would have commenced at still lower values of PIFR. Most adults produce PIFR on the falling part of these curves, and the mask is therefore behaving in a variable manner.

On the basis of these findings certain suggestions may be made regarding the use of venturi-type masks in general, and the Hudson Multivent mask in particular.

(1) Predictable function cannot be assumed without knowledge that the total gas flow is about 30% above the PIFR of the recipient.

(2) To this end, for an average man, breathing quietly, the following settings may be recommended:

24% at 3 l/min supplied-oxygen flow rate
26% at 6 l/min supplied-oxygen flow rate
28% at 6 l/min supplied-oxygen flow rate
30% at 9 l/min supplied-oxygen flow rate

(3) At the 35%, 40% and 50% settings, the mask is variable in performance, unless low PIFR occurs.

It should be stressed that few patients requiring controlled inspired oxygen therapy are healthy males breathing quietly. If hyperventilation is present the recommended values may need to be increased.

CONCLUSIONS

1. Predictable inspired oxygen concentrations using the Hudson Multivent mask cannot be assumed unless account has been taken of the total gas delivery rate to the mask, and the PIFR of the recipient.

2. On the settings of the mask up to 30% oxygen, predictable inspired oxygen concentrations may be obtained by increasing the supplied-oxygen flow rate above the recommended value.

3. On settings above 30% oxygen predictable function is unlikely to be obtained, even by these means.

ACKNOWLEDGEMENTS

We wish to thank Dr. J. Gibbs and Dr. F. M. Davis for their advice and support during the preparation of this manuscript. We are also indebted to Dr. H. Guy for his advice regarding equipment, to Mr. D. Radford for the use of his computer program, and to Miss J. Larsen for typing the document.

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