APPARATUS

# Evaluation of five oxygen delivery devices in spontaneously breathing subjects by oxygraphy

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**Summary**

Oxygen supply systems may be divided into constant and variable performance systems. As the variable performance systems are widely used, it is relevant to investigate the variation in performance between devices and the influence of oxygen supply on the inspired oxygen fraction. Data were collected from 10 healthy volunteers during the use of one constant performance system and four variable performance systems at different gas flows and inspired oxygen fractions. A thin sampling catheter was placed in the nasopharynx to allow the measurement of the end-tidal oxygen fraction. When oxygen was supplied to variable performance systems, end-tidal oxygen fraction values measured in this way varied less and were more easily quantifiable than inspired oxygen fraction. End-tidal oxygen fraction was used to calculate inspired oxygen fraction. With the variable performance systems, inspired oxygen fraction varied considerably between subjects whereas a constant and equal rise was found for each subject with the fixed performance system. A large nasal catheter was capable of delivering the highest inspired oxygen fraction, whereas the Venturi mask delivered the most precise inspired oxygen fraction. We found oxygraphy useful in the interpretation of measurements made in patients receiving unknown inspired fractions of oxygen.

**Keywords** *Equipment*; oxygen delivery systems.

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Oxygen has been an indispensable therapeutic drug since the beginning of the 19th century [1]. A wide variety of oxygen delivery systems are available. Leigh [1] has divided these into fixed and variable performance systems. The former provide a constant inspired oxygen fraction ($F_{I}O_2$) which is independent of patient ventilation characteristics and the latter provide a variable $F_{I}O_2$ which is dependent on the patient's ventilation. Consequently, the $F_{I}O_2$ provided by the constant performance systems can be predicted accurately but this is not the case for the variable performance systems. Nevertheless, the variable performance systems have gained great popularity owing to their low cost and greater patient comfort.

As the variable performance systems are widely used it is relevant to evaluate the variation in performance between devices and the influence of oxygen supply on the $F_{I}O_2$. The efficacy of oxygen therapy can be evaluated by a number of methods that reflect different steps in the oxygenation process depending on the sampling site. Modern gas analysers can provide a continuous recording of oxygen fraction ($FO_2$) from both intubated and non-intubated patients. Compared with former studies, when gas was sampled at a fixed phase of the respiratory cycle [2–7], modern oxygraphs can follow the changes in $FO_2$ during the entire respiratory cycle. Thus, oxygraph recordings of $FO_2$ allow comparison of the function of different oxygen delivery systems. Fluctuations of $F_{I}O_2$ and their relation to the end-tidal oxygen fraction ($F_{E'}O_2$) are of particular interest. Arterial blood gas analysis is frequently used when close monitoring of oxygen therapy is indicated [8, 9].

The aims of this study were to describe the $FO_2$ throughout the entire respiratory cycle using five different oxygen delivery devices, to evaluate the effect of the oxygen delivery systems on $F_{E'}O_2$ and to calculate mean values of $F_IO_2$ for the oxygen delivery systems.

## Methods

Ten subjects (five women and five men) were recruited to the study after giving informed consent. The Ethics Committee of Copenhagen County approved the study. All subjects were healthy and had no history of pulmonary disease. Demographic data and the results of pulmonary function tests are presented in Table 1.

A Brüel & Kjær (B&K) multigas monitor 1304 (Copenhagen, Denmark) was used to measure $FO_2$. The B&K 1304 is a side stream analyser that uses a combination of paramagnetic and acoustic techniques for oxygen measurement [10]. The monitor has a response time of less than 250 ms and the device used had demonstrated high reliability and precision in oxygen measurement with an error less than 1% of full scale. Before each set of measurements the monitor was calibrated using B&K calibration gas (QA 0207). The sampling system consisted of a polyvinyl chloride catheter (Unoplast, Hundested, Denmark) connected to the B&K 1304 by a 2.4-m tubing system (UA 1166). The delay time with this tubing system was 2.5 s at a sample flow of 90 ml.min$^{-1}$. A printer (UP 850 Sony, Japan) provided hard copy of the monitor display.

Oxygen was supplied to the volunteers by five different systems. The time constant of each system was determined in each subject and was defined as the time from the start of an abrupt change of the delivered oxygen flow until 63% of the new steady state had been achieved.

Five oxygen delivery systems were studied:

**1** The small nasal catheter (Unoplast A/S, Denmark), a unilateral nasal catheter, consists of a 40-cm soft plastic tube with an internal diameter of 3 mm. The distal 1.5 cm of the catheter is nylon foam-collared and is inserted into the nostril. The measured time constant was found to range from 1.3 to 2.3 min at an oxygen flow of 6 l.min$^{-1}$. The small nasal catheter was studied with oxygen flows of 2, 4 and 6 l.min$^{-1}$.

**2** The nasal cannula (Unoplast A/S, Denmark), a bilateral nasal catheter (i.e. nasal cannulae), consists of a plastic tube with an internal diameter of 6 mm which has two prongs that project about 1 cm into the nose on both sides. The measured time constant was found to range from 1.3 to 1.9 min at an oxygen flow of 6 l.min$^{-1}$. The nasal cannula was studied with oxygen flows of 2, 4 and 6 l.min$^{-1}$.

**3** The Hudson mask (Hudson RCI, Mexico) consists of a vented enclosure applied over the nose and mouth. Oxygen–air mixtures were delivered through a 27-cm catheter with an internal diameter of 6 mm (Catheters & Tubes, Denmark) with a distal nylon foam-collared end which was inserted into the opening of the mask. The proximal end of the catheter was connected to a heated humidifier (Ohmeda, USA) via a 160-cm corrugated tube (Polystan, Denmark) [11]. The measured time constant was found to range from 1.4 to 2.0 min at a flow of 30 l.min$^{-1}$. A mixture of oxygen and air was delivered to the volunteers at varying $FO_2$ values at a total gas flow of 15 and 30 l.min$^{-1}$.

**4** The large nasal catheter consisted of the same gas delivery system as described for the Hudson mask. However, the gas was delivered directly to one of the nostrils with the foam-collared end of the nasal catheter inserted into the nostril and not through the Hudson mask. The measured time constant was found to range from 1.4 to 2.5 min at a flow of 30 l.min$^{-1}$. A mixture of oxygen and air was delivered to the volunteers at varying $FO_2$ values at a total gas flow of 15 and 30 l.min$^{-1}$.

**5** Venturi masks (Medic-Aid, UK) supplying 24, 28 and 40% oxygen were used. The measured time constant for the 40% oxygen mask was found to range from 1.0 to 1.6 min The highest oxygen flows recommended by the manufacturers were used.

Gas flow was measured with Rotameters (Ohio Medical products, USA) which were calibrated with a spirometer. A pressure-compensated flow meter (Ohio Medical products, USA) was used to deliver oxygen to the Venturi systems.

A polyvinyl chloride sampling catheter was advanced at least 10 cm through one nostril into the subject's nasopharynx to a position that caused minimal discomfort. The catheter was then connected to the B&K 1304 gas analyser. Earlier studies have demonstrated that this measurement method is reliable [12–14]. The subjects were studied while lying supine. The five oxygen delivery systems and the different gas flows were administered in random order according to 10 predetermined schemes. The measurements were taken when the subjects appeared relaxed and had a stable respiratory rate. Simultaneously, a blood sample was drawn from a cannula placed in the radial artery and analysed by an ABL 520 (Radiometer Medical, Copenhagen) blood gas analyser. A period equal to at least two time constants was allowed to pass between each investigation period.

**Table 1** Demographic data and pulmonary function in the 10 subjects.

| | Age; years | Weight; kg | Height; cm | $FEV_1$; l | VC; l |
|---|---|---|---|---|---|
| Mean | 32.6 | 69.7 | 174 | 3.78 | 4.69 |
| Range | 23–47 | 56–87 | 163–184 | 2.6–5.1 | 3.6–6.2 |

VC: vital capacity. $FEV_1$: forced expiratory volume in 1 s.

The curves and measured values were recorded by copying the display of the B&K 1304 to the printer. The display of the B&K 1304 included curves of the preceding 22.5 s and provided inspiratory and end-tidal $F_{O_2}$ values calculated as the mean of the preceding eight respiratory cycles. The phases of the respiratory cycle were assessed according to the carbon dioxide curve.

For devices receiving oxygen/air mixtures, the delivered oxygen fraction was calculated from the settings of oxygen and air on the flow meters. The $F_{O_2}$ values are given at standard temperature and pressure of dry air (STPD).

The best estimates of $F_{IO_2}$ based on measured $F_{E'O_2}$ were calculated using the alveolar gas equation:

$$F_{AO_2} = F_{IO_2} - (F_{ACO_2}/RQ) \times (1 - F_{IO_2}(1 - RQ)) \ [15]$$

where $F_{ACO_2}$ is the alveolar fraction of carbon dioxide and $RQ$ is the respiratory quotient. Assuming that $F_{AO_2} = F_{E'O_2}$ and that equilibrium of alveolar and arterial carbon dioxide is achieved, the equation can be rearranged as:

$$F_{IO_2} = (F_{E'O_2} \times RQ + F_{ACO_2})/(RQ + F_{ACO_2} \times (1 - RQ)).$$

The results were separated into groups according to the supply system and oxygen flow. Within each group means and standard deviations (SD) were calculated. Comparable groups were tested against each other using paired *t*-tests. Probability values less than 0.05 were considered to be significant.

## Results

The oxygen curves in the variable performance systems show characteristic variations during the inspiratory phase (Fig. 1). The inspired oxygen fraction increased in the initial phase of the inspiration towards 100% and decreased abruptly in the middle of inspiration. A second rise was observed before expiration, frequently resulting in an M-shaped inspiratory waveform. There seemed to be a high within-subject variation in the curves during the inspiratory phase, especially with the small nasal catheter, the nasal cannula and the large nasal catheter but no quantitative assessment of the $F_{O_2}$ against time can be given with

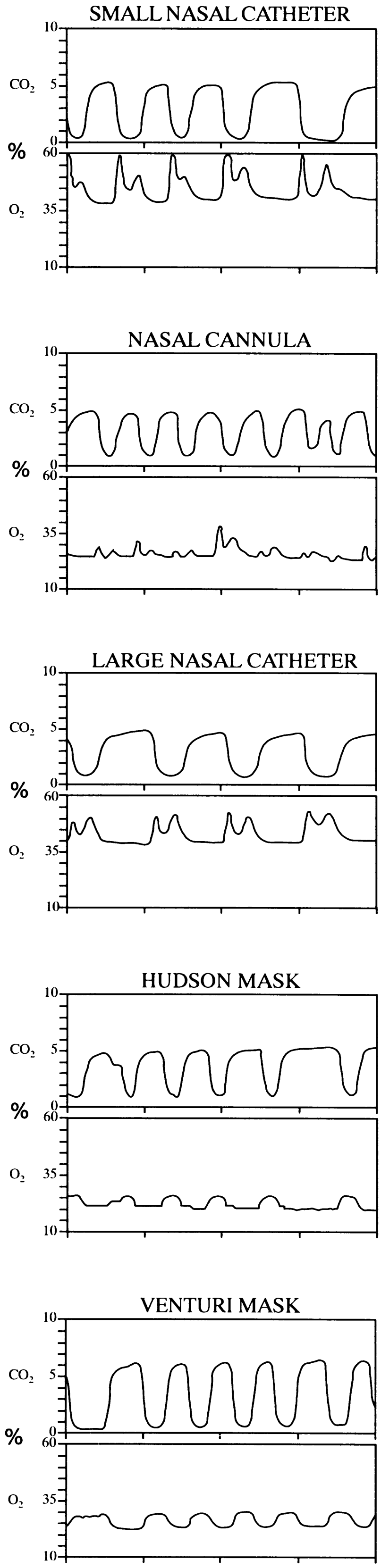


**Figure 1** Oxygen and carbon dioxide waveforms during the use of the five oxygen delivery systems. Small nasal catheter: oxygen 6 l.min$^{-1}$, nasal cannula: oxygen 2 l.min$^{-1}$, large nasal catheter: delivered oxygen fraction 0.6 at 15 l.min$^{-1}$, Hudson mask: delivered oxygen fraction 0.37 at 15 l.min$^{-1}$, 28% oxygen Venturi mask.

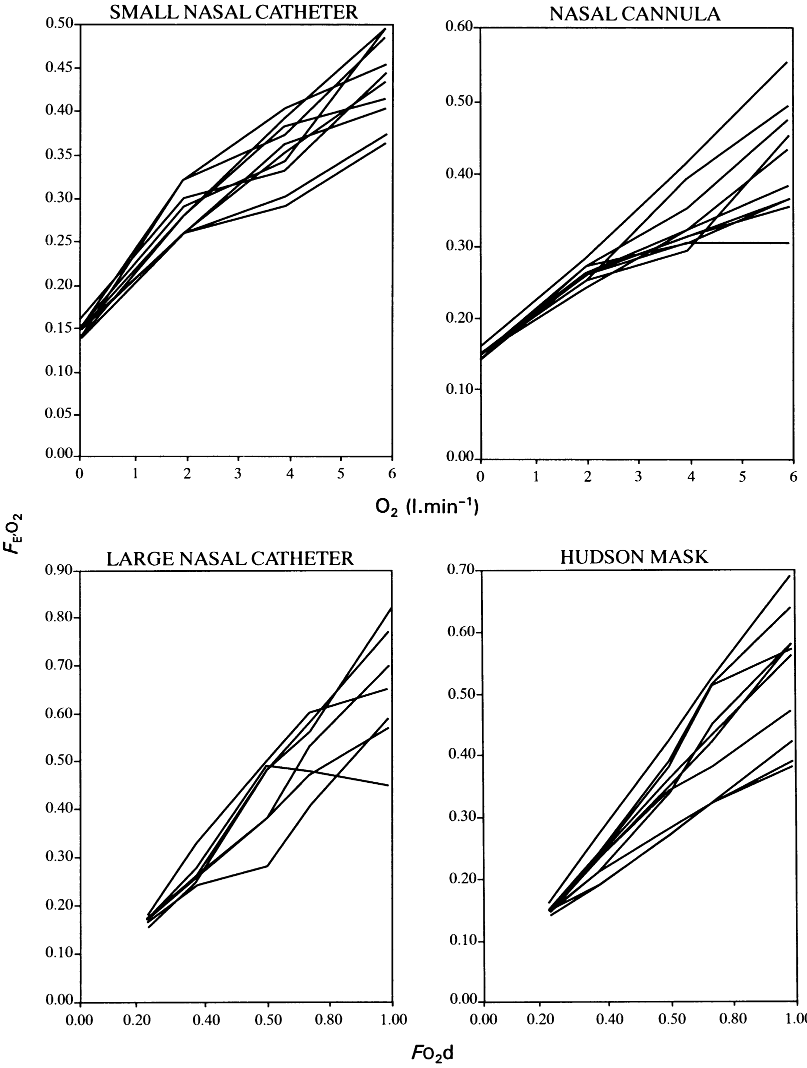


**Figure 2** Expired oxygen fraction plotted against oxygen flow or delivered oxygen fraction ($FO_2$d) for the variable performance systems studied.

this experimental setup. Smaller fluctuations were observed in the oxygen curve during the inspiratory phase with the Hudson mask and the Venturi mask. When oxygen was supplied through the small nasal catheter the B&K monitor displayed a higher $F_{E'}O_2$ than $F_IO_2$ in eight out of the 10 subjects.

Figure 2 shows $F_{E'}O_2$ for each subject with the four variable performance systems at different oxygen flows and delivered $FO_2$. The rise in $F_{E'}O_2$ with oxygen supply was evident but the scatter between the subjects increased with increasing oxygen flow or delivered $FO_2$. The Venturi system (Fig. 3) was characterised by a constant and equal rise with increasing $F_IO_2$. There was little between-patient variation.

Mean $F_{E'}O_2$ and calculated $F_IO_2$ values corresponding to Figs 2 and 3 are listed in Tables 2, 3 and 4. At an oxygen flow of 2 l.min$^{-1}$, there was a small but statistically significant difference in $F_{E'}O_2$ between the small nasal catheter and the nasal cannula. The large nasal catheter showed a significantly higher $F_{E'}O_2$ at most flows when compared with the Hudson mask. The highest $F_{E'}O_2$ (0.86) was obtained with the large nasal catheter.

## Discussion

Evaluation of oxygen therapy by fast response oxygen analysers has been possible for at least 25 years. Leigh [16] demonstrated the characteristic oxygen curves of constant and variable performance systems. The present study has confirmed Leigh's observations but the improved gas analysers have made it possible for us to collect more extensive information about $FO_2$ in the entire respiratory cycle in normal subjects during treatment with five different oxygen delivery systems. The high variability in

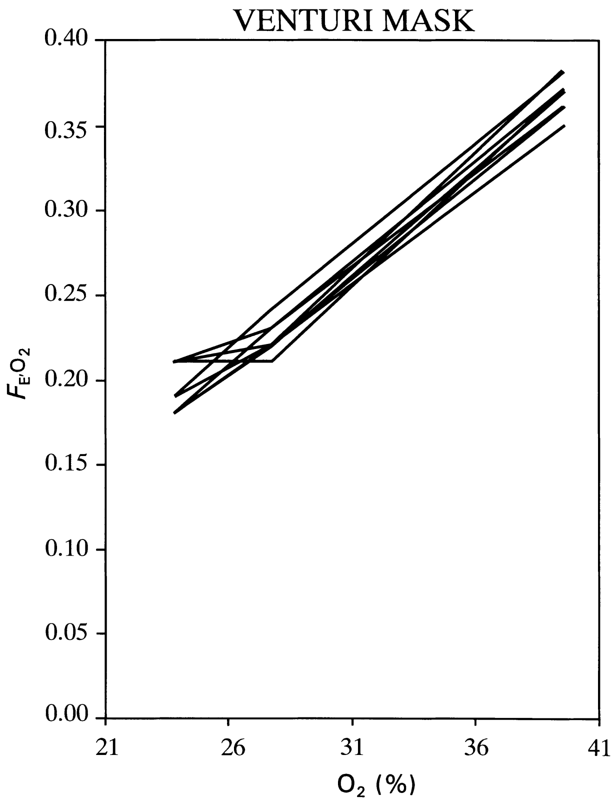


**Figure 3** Expired oxygen fraction plotted against set oxygen percentage for the Venturi masks.

$F_IO_2$ suggests that the values provided automatically by the B&K 1304 should not be used as a quantitative measure of the effect of oxygen supply on $F_IO_2$. The $F_IO_2$ displayed by the B&K 1304 is taken at a single point (the oxygen fraction at the lowest carbon dioxide value) in the fluctuating inspiratory phase. We used end-tidal values to demonstrate the differences in $F_AO_2$ and to calculate $F_IO_2$ from the alveolar air equation. In healthy subjects it is reasonable to assume that the end-tidal sample is representative of alveolar gas concentrations [17].

A disadvantage of side stream analysers is occlusion by saliva and other secretions. From earlier studies [14] we have observed that saliva tends to occlude the sampling tube system and interrupts the recordings. This problem was overcome by placing a filter between the polyvinyl chloride catheter and the system tubing with the result that saliva accumulated in the filter instead of the tubing system.

Different classification systems of oxygen delivery devices have been proposed. Leigh's distinction between constant and variable performance systems has the advantage that it is based on variability in $F_IO_2$ during the inspiratory phase of the respiratory cycle. Other authors [18, 19] have classified delivery devices into high and low flow systems. This classification is similar to Leigh's classification because a constant $F_IO_2$ is observed when the supplied flow is high (i.e. when the device delivers at least four times the patient's minute volume), whereas $F_IO_2$ fluctuates when the supplied flow is low and ambient air is therefore admixed in different proportions. However, the results from the Hudson mask in our study demonstrate that there may be a relatively high flow through a supply system without the expected effect on $F_IO_2$. The reason for this contradiction is the difficulty in supplying the air stream of the oxygen therapy system directly to the inspiratory air stream of the subject. In consequence, we consider the classification of Leigh the more appropriate.

The oxygen tracings in Fig. 1 demonstrate the differences between the systems. The small nasal catheter, nasal cannula and the large nasal catheter have an oxygen waveform that is typical for a variable performance system [1]. The M-configuration during inspiration illustrates that the subjects' inspiratory flow exceeds that of the supplied flow. The first peak is produced by a high oxygen concentration initially present in the upper airway. This small reservoir of oxygen is moved to the lower airway during the early inspiratory phase. The subsequent decline is caused by increased atmospheric air admixture causing the $F_IO_2$ to decrease. The second smaller peak is due a relatively higher concentration of oxygen during the decrease of flow in the later phase of inspiration. In

**Table 2** Measured and calculated oxygen fractions for the small nasal catheter and nasal cannula. Gas supply to these devices was 100% oxygen. Values are given as mean (SD).

| | Oxygen supply to small nasal catheter; $l.min^{-1}$ | | | Oxygen supply to nasal cannula; $l.min^{-1}$ | | |
|---|---|---|---|---|---|---|
| | 2 | 4 | 6 | 2 | 4 | 6 |
| $F_{E'}O_2$ | 0.28 (0.024)* | 0.35 (0.037) | 0.43 (0.047) | 0.26 (0.012) | 0.33 (0.041) | 0.41 (0.076) |
| Calculated $F_IO_2$ | 0.35 | 0.42 | 0.50 | 0.33 | 0.40 | 0.48 |

* Significantly different from nasal cannula value, $p < 0.05$. $F_{E'}O_2$ and $F_IO_2$: expired and inspired oxygen fraction.

**Table 3** Measured and calculated oxygen fractions for the large nasal catheter and Hudson mask. Oxygen fraction values are given as mean (SD).

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Oxygen flow; $l.min^{-1}$ | 0 | 3 | 7.5 | 10 | 15 | 0 | 12 | 30 |
| Air flow; $l.min^{-1}$ | 15 | 12 | 7.5 | 5 | 0 | 30 | 18 | 0 |
| Delivered $F_{O_2}$ | 0.21 | 0.37 | 0.60 | 0.74 | 1.0 | 0.21 | 0.52 | 1.0 |
| *Large nasal catheter* | | | | | | | | |
| $F_{E'O_2}$ | 0.17 (0.011)* | 0.27 (0.029)* | 0.44 (0.058)† | 0.52 (0.068)* | 0.65 (0.13) | 0.16 (0.009)* | 0.42 (0.056)* | 0.86 (0.065)† |
| Calculated $F_{IO_2}$ | 0.23 | 0.34 | 0.51 | 0.58 | 0.71 | 0.23 | 0.48 | 0.92 |
| *Hudson mask* | | | | | | | | |
| $F_{E'O_2}$ | 0.15 (0.007) | 0.23 (0.025) | 0.34 (0.052) | 0.42 (0.081) | 0.53 (0.11) | 0.15 (0.009) | 0.33 (0.057) | 0.58 (0.14) |
| Calculated $F_{IO_2}$ | 0.21 | 0.29 | 0.41 | 0.48 | 0.59 | 0.22 | 0.39 | 0.65 |

*Significantly different from Hudson mask value, $p < 0.05$; †significantly different from Hudson mask value, $p < 0.01$. $F_{E'O_2}$ and $F_{IO_2}$: expired and inspired oxygen fraction.

eight subjects, $F_{E'O_2}$ was higher than the $F_{IO_2}$ when oxygen was delivered by the small nasal catheter. This was also the case in a few measurements when oxygen was delivered via the large nasal catheter. This phenomenon is obviously a physiological impossibility. A possible explanation for this paradox is that the sampling catheter is not placed centrally in the inspiratory air stream. This phenomenon also suggests that $F_{E'O_2}$ is the best parameter to evaluate different oxygen delivery devices.

The fluctuations in the oxygen curve during the inspiratory phase are less pronounced with the Hudson mask compared with the nasal systems but the $F_{E'O_2}$ is not as predictable (Fig. 2) as with the Venturi system (Fig. 3). The oxygen waveform of the Venturi mask is typical for a constant performance system. In contrast to the variable performance systems, the supplied gas flow exceeds the inspiratory flow. The $F_{IO_2}$ achieved by the Hudson mask is significantly lower than that provided by the large nasal catheter with identical delivered $F_{O_2}$ and flows. The Hudson mask is open to the atmosphere through two orifices and a great deal of oxygen is probably lost through the mask and therefore the $F_{IO_2}$ becomes lower than expected. The significantly higher $F_{E'O_2}$ value obtained with the large nasal catheter supplying atmospheric air is probably due to the continuous positive airway pressure induced by the high flow rate. The large nasal catheter was capable of delivering a high $F_{IO_2}$ and a high $F_{E'O_2}$ was achieved. This can be explained by direct delivery of the high oxygen flow to the airway and the reservoir of oxygen in the airway produced during the expiratory pause. The variability of the four variable performance systems increases with the delivered $F_{O_2}$ and flows except when oxygen is delivered via the large nasal catheter at a flow of 30 $l.min^{-1}$. This is probably due to a greater displacement of atmospheric air implying that the delivered air mixture will have a greater and more constant impact.

**Table 4** Measured and calculated oxygen fractions for the Venturi masks. Oxygen fraction values are given as mean (SD).

| | **Set $F_{IO_2}$ on Venturi mask** | | |
|---|---|---|---|
| | **0.24** | **0.28** | **0.40** |
| $F_{E'O_2}$ | 0.20 (0.013) | 0.23 (0.008) | 0.37 (0.009) |
| Calculated $F_{IO_2}$ | 0.27 | 0.29 | 0.43 |
| Measured $F_{IO_2}$ | 0.25 | 0.29 | 0.43 |

$F_{E'O_2}$ and $F_{IO_2}$: expired and inspired oxygen fraction.

Both the subject and device are significant factors in the effect of oxygen therapy. The important subject factors are probably the inspiratory flow rate, minute ventilation and the expiratory pause. The device factors are oxygen flow, physical volume and the type of air stream supplied [1]. Since the respiratory cycle, the inspiratory flow rate and the exact position of the device vary between subjects, it is not surprising that the performance of the systems differed between individuals in our study. Although measurements of $F_{O_2}$ were not recorded until values were seen to be stable on the B&K monitor and the subjects were breathing normally, no other attempts were made to control the breathing pattern of the individual subject. We wanted our study design to mimic real life conditions. In an earlier study we have shown that nose or mouth breathing had no influence on the recorded gas values [14], which has been confirmed by Kory *et al.* [2]. As expected, subject factors did not influence the $F_{O_2}$ significantly when oxygen was delivered through the Venturi mask.

The results obtained in our study may be difficult to compare with those published in other studies. This is due to the different measurement methods, flows, sampling sites, ventilation pattern of the subjects and the inherent problems in determining $F_{IO_2}$. However, in agreement with other studies [2, 20], we have demonstrated that the small nasal catheter is slightly more effective than the nasal cannula. The use of the large nasal catheter resulted in a significantly higher $F_{E'}O_2$ compared with the Hudson mask [21]. In agreement with other studies [6, 8], we found that the $F_IO_2$ using the Venturi mask is almost equal to that which is indicated on the Venturis, suggesting that the flow is adequate. The calculated $F_IO_2$ values are in good agreement with the measured $F_IO_2$, suggesting that the assumed respiratory quotient value of 0.86 is appropriate. We believe that calculation of $F_IO_2$ is the best approximation to the truth. The number of assumptions is modest and the values that are included in the alveolar gas equation are measured in each subject.

The choice of oxygen delivery system depends on the type of ventilatory failure. If the therapeutic aim is to provide a precise $F_IO_2$, the constant performance system is the best choice. If a high alveolar $FO_2$ is the goal, the large nasal catheter seems to be the best choice. The patient's compliance with the device is another factor to take into account. Stausholm *et al.* evaluated three devices (nasal cannula, nasal catheter and Hudson mask) in the late postoperative period [22]. They found that patients experienced more comfort and satisfaction with the nasal cannula and catheter than with the Hudson mask.

Modern blood gas analysers can be programmed to calculate the alveolar to arterial oxygen difference and shunt fraction in order to assess pulmonary function. To provide a reliable measure of the difference or shunt, accurate estimates of $F_IO_2$ or $F_{E'}O_2$ are necessary. A study comparing healthy subjects and patients with chronic obstructive airways disease demonstrated that the differences in $F_IO_2$ values obtained with the nasal cannula (at oxygen flows of 1 and 2 $l.min^{-1}$) were not significantly different between the two groups, although alveolar emptying in the chronic obstructive airway disease group was expected to be abnormal. However, the $FO_2$ values in our study assume normal ventilation which is not always present in clinical situations and extrapolation to the clinical situation should be performed with caution.

Continuous monitoring of oxygen in the airway is informative in determining the efficacy of oxygen therapy and allows the calculation of pulmonary indices of oxygenation. The measurement methods described in this paper cannot substitute for blood gas measurements. However, oxygraphy appears useful when interpretation of measurements is made on patients receiving unknown concentrations of oxygen. Precise determination of $F_{E'}O_2$ can be carried out and, combined with arterial blood gas analysis, a reliable evaluation of pulmonary gas exchange can be carried out with calculation of the intrapulmonary shunt fraction by computer programs (e.g the Oxygen Status Algorithm) [23].

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