INCREASED VENTILATION REQUIREMENTS DURING OBSTETRIC GENERAL ANAESTHESIA

A. J. RAMPTON, S. MALLAIAH AND C. P. O. GARRETT

During pregnancy metabolic rate and carbon dioxide production increase by 30–33% [1–3]. In addition, hyperventilation occurs, causing a reduction in arterial carbon dioxide tension (\(P_{aCO_2}\)) to 3.9–4.2 kPa [4–6]. These effects are present by 12 weeks gestation, possibly having begun within days of conception. Both these factors produce an increase in the awake resting minute volume of the pregnant patient of between 42% and 57% [1–4]. Much more marked hyperventilation can occur during labour. These metabolic and respiratory changes persist for 2–14 days post-partum [1,2,5].

Much has been written as to the possible beneficial or detrimental effects on the fetus of hypercapnoea and hypocapnoea, both during labour and during general anaesthesia for operative delivery. However, it is now generally accepted that it is probably best to try and reproduce the physiological carbon dioxide tension of 4 kPa.

Although the physiological changes in metabolism and ventilation that occur during pregnancy are widely appreciated, until recently little has been published on determining how large an increase in ventilation is required during obstetric general anaesthesia. This study was undertaken to determine what increase in inspiratory fresh gas flow (FGF) is required in pregnant patients, during general anaesthesia (associated with neuromuscular blockade and artificial ventilation) to produce a carbon dioxide tension of 4 kPa. Since metabolic rate is related to age and sex in addition to body mass [7], a group of obstetric patients was compared with a group of non-pregnant female patients of a similar age range, undergoing gynaecological surgery. End-tidal expired carbon dioxide tension (\(P_{ETCO_2}\)) was used as an indicator of \(P_{aCO_2}\).

**SUMMARY**

The inspiratory fresh gas flow rate (FGF) required to produce an end-tidal carbon dioxide tension (\(P_{ETCO_2}\)) of 4 kPa during general anaesthesia, neuromuscular blockade and artificial ventilation, was compared in a group of 46 obstetric patients and a matched group of 50 non-pregnant female patients. The non-pregnant patients required a mean (SD) inspiratory FGF of 77 (10.6) ml kg\(^{-1}\) min\(^{-1}\), whereas the pregnant patients required a mean FGF of 121 (24.6) ml kg\(^{-1}\) min\(^{-1}\) before delivery (in those who reached a stable state), and 109 (19.3) ml kg\(^{-1}\) min\(^{-1}\) after delivery. These represent significant (P < 0.0001) increases of 57% and 42%, respectively, over the non-pregnant state.

**PATIENTS AND METHODS**

**Patients**

The obstetric patient group comprised 46 patients having elective or emergency operative delivery under general anaesthesia, the majority having Caesarean section, a small proportion having forceps delivery. The non-pregnant patient group comprised 50 female patients aged up to 45 yr, receiving general anaesthesia for elective gynaecological surgery. Patients were excluded if they had any symptoms or clinical evidence of cardiovascular, respiratory or metabolic disease, and if they were febrile.
Anaesthetic technique

The anaesthetic technique for the obstetric patients consisted of premedication with antacid only, pre-oxygenation, cricoid pressure and rapid sequence induction with thiopentone i.v. Suxamethonium was administered and, after intubation of the trachea, anaesthesia was maintained until delivery with 50% nitrous oxide and 0.5% halothane in oxygen. Atracurium was given to provide muscle paralysis. After delivery the halothane was discontinued, the nitrous oxide concentration was increased to 70%, and an opioid was administered i.v. The non-obstetric patients were all premedicated with papaveretum and hyoscine, and received thiopentone, fentanyl and atracurium at induction of anaesthesia, which was maintained with 70% nitrous oxide and 0.5% halothane or 1.0% enflurane in oxygen.

The ventilator used for all patients was a Medishield Manley Pulmovent MPP with a standard black rubber patient breathing system. The volume of the breathing system and catheter mount was 1025 ml by water displacement. Tidal volumes (as measured by a Wright's respirometer) were adjusted to between 10 and 15 ml kg⁻¹ up to a maximum of 1000 ml. Maximum airway pressures measured by the gauge on the ventilator ranged from 18 to 24 cm H₂O for all the patients studied. The obstetric patients had a 15° left lateral tilt before delivery and were supine after delivery. The gynaecological patients were supine at the time that the ventilatory measurements were made.

Ventilatory measurements

$P_{\text{E}_\text{CO}_2}$ was measured using a Datex CD102 capnograph, sampling from the centre of an adaptor mounted on the tracheal tube connector, at a flow rate of 50 ml min⁻¹. For the first 50 patients, the capnograph was zeroed and calibrated (using Datex calibration gas) for every patient. The capnograph proved to be very stable and, subsequently, was re-zeroed for every patient but only recalibrated at intervals. In all patients the rotameter flow rates were adjusted until a stable $P_{\text{E}_\text{CO}_2}$ of 4 kPa was obtained. In order to obtain a stable value during the induction to delivery period in the obstetric patients, this sometimes required adjustment of the flow rate every 1–2 min. In the non-pregnant patients, and after delivery in the obstetric patients, there was little problem achieving a steady state, and flow rate recordings were made towards the end of the surgical procedure.

Considerable time was spent on selecting a method for measuring the required FGF. A technique was needed which would give a steady flow rate reading from the pulsatile flow output from the ventilator. In addition, it was necessary to obtain readings in a short period for the frequently unstable pre-delivery values. Use of a pneumotachograph was excluded because of the long warm up time required (50% of the obstetric patients were having unplanned emergency procedures). Attempts to measure cumulative inspiratory gas volume over precisely timed intervals using mechanical and electronic Wright's respirometers and a Drager volumeter gave very inaccurate results, probably as a result of the rapid initial flow rate at the onset of the inspiratory phase. In addition, this method was sometimes impractical, with frequently adjusted flow rates in the period before delivery in the obstetric patients.

Eventually, it was decided that during each anaesthetic we would simply record the flow rate readings from the rotameters at the point when $P_{\text{E}_\text{CO}_2}$ was stable at 4.0 kPa. In addition, at intervals during the study we assessed the accuracy of the rotameters and confirmed that there were no leaks in the anaesthetic machines, ventilators and breathing systems that were used. Subsequently, we also determined and applied correction factors for the errors from ventilator back pressure and compliance of the ventilator and its circuit.

The accuracy of the rotameters was assessed at intervals during the study over the range of 4–14 litre min⁻¹ of 50% nitrous oxide in oxygen by comparing their flow rates (with no back pressure applied) against those from a regularly calibrated GEC Elliot 1100 reference rotameter. Testing for leaks at similar intervals excluded any greater than 250 ml min⁻¹. Determination of correction factors for the two errors mentioned above was performed using a Mercury Electronics CS5 pneumotachograph connected to a Gould MK220 chart recorder. Error from back pressure was determined by comparing flow rates at the common gas outlet for a constant rotameter setting with and without ventilator back pressure applied. Errors from compliance were determined by comparing gas flow at the input to the ventilator with those at the distal end of the catheter mount, both with patients and with a Medishield Lung Simulator (using a range of tidal volumes of
500–1000 ml and a range of lung compliances of 50–20 ml \( (cm \text{ H}_2\text{O})^{-1} \). These determinations of the necessary correction factors were repeated on three occasions, using gas flows of 4, 6, 8, 10, 12 and 14 litre min\(^{-1}\). The required correction factors were obtained from the ratio of the slopes of cumulative volume against time (thus converting any pulsatile flow to a constant value). No attempt has been made to adjust for variations in ambient pressure or temperature, gas sampling or the addition of the inhalation agent.

With the prior verbal consent of eight of the obstetric patients, a single arterial blood sample (radial artery) was taken at a point when \( P_{\text{E}}'\text{CO}_2 \) was stable, to determine the arterial to end-tidal carbon dioxide tension gradient \( (P_{\text{a}}\text{CO}_2 - P_{\text{E}}'\text{CO}_2) \).

**Analysis of results**

Linear regression equations were derived for the correction factors for back pressure on the rotameters and the compliance of the ventilator and breathing system. Linear regression and correlation analyses were performed for the FGF results against the patients' age, weight, height and body surface area. Statistical comparisons between groups were performed using Student's paired or unpaired \( t \) test as appropriate.

**RESULTS**

Details of the patients are given in table I. Body surface area was estimated from a standard nomogram [7] (possibly inappropriate for pregnant patients). There were no significant differences between the two groups \( (P > 0.05) \) for age, height, weight and estimated body surface area (using the weight of the obstetric patients at the time of the first ante-natal visit).

The \( P_{\text{a}}\text{CO}_2 - P_{\text{E}}'\text{CO}_2 \) gradient measurements in eight obstetric patients showed a mean value of 0.09 kPa (range \(-0.16 \) to \(+0.36 \) kPa).

Assessment of accuracy of the rotameters on all the anaesthetic machines used showed mean (SD) errors of \(-1.6 \) (2.6)\% with a range of \(-5.1 \) to \(+3.6 \)\%. No correction has been made for these errors, since they were randomly spread around a mean of near zero. Assessment of rotameter under-reading as a result of back pressure gave a regression equation of: Actual gas flow = rotameter reading \( \times (1.028 + \text{rotameter reading} \times 0.00077) \); thus rotameter under-reading ranged from 3.1\% at 4 litre min\(^{-1}\) to 3.9\% at 14 litre min\(^{-1}\). These figures are slightly lower than the theoretically predicted values (the back pressure from a Manley Pulmovent MPP varies from approximately 85 mm Hg at 4 litre min\(^{-1}\) to 120 mm Hg at 14 litre min\(^{-1}\)). Assessment of gas loss in the ventilator and its circuit gave a regression equation of: Actual inspiratory gas flow = FGF to ventilator \( \times (0.963 - \text{FGF to ventilator} \times 0.0082) \), thus giving a gas loss which ranged from 7.0\% at 4 litre min\(^{-1}\) to 15.2\% at 14 litre min\(^{-1}\). All the FGF quoted below are the values after correction with these two regression equations.

Figures 1 and 2 show scatter plots for the FGF results against body weight and estimated body surface area, respectively. Correlation coefficients for the FGF results against age, height, weight and estimated body surface area were 0.11, 0.49, 0.55 and 0.57, respectively, for the post-delivery values in the obstetric patients, and 0.01, 0.20, 0.57 and 0.58, respectively, in the non-pregnant patients. Thus age and height are very poor predictors of the required FGF, weight and body surface area being considerably better. Since body surface area may not always be available to the anaesthetist, the only FGF rates discussed subsequently are those expressed in terms of ml kg\(^{-1}\) min\(^{-1}\).

The mean FGF results for each group are given in table II. The mean FGF rate in the non-pregnant patients was 77 ml kg\(^{-1}\) min\(^{-1}\), and in the obstetric patients after delivery was 109 ml kg\(^{-1}\) min\(^{-1}\). In 30 of the 46 obstetric patients a roughly stable pre-delivery mean value of 121 ml kg\(^{-1}\) min\(^{-1}\) was obtained—12 ml kg\(^{-1}\) min\(^{-1}\) greater than the values after delivery in the same 30 patients. Both pre- and post-delivery minute volumes were significantly different from those for the non-pregnant patients \( (P < 0.0001) \). The spread of results was slightly greater for the obstetric patients.

**Table I. Demographic data for the patients studied.**

<table>
<thead>
<tr>
<th></th>
<th>Obstetric patients ( (n = 46) )</th>
<th>Non-pregnant patients ( (n = 50) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>30.4 (7.0)</td>
<td>33.0 (6.4)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.60 (0.07)</td>
<td>1.62 (0.07)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>At operation</td>
<td>71.0 (15.0)</td>
<td>64.2 (10.8)</td>
</tr>
<tr>
<td>At first ante-natal visit</td>
<td>61.6 (14.0)</td>
<td>73.2 (17.0)</td>
</tr>
<tr>
<td>Estimated surface area (m(^{2}))</td>
<td>1.73 (0.19)</td>
<td>1.68 (0.13)</td>
</tr>
<tr>
<td>Gestation (weeks)</td>
<td>37.1 (4.1)</td>
<td>30.4 (7.0)</td>
</tr>
<tr>
<td>Number in labour</td>
<td>23 (50%)</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1. Inspiratory fresh gas flows required for an end-tidal carbon dioxide tension of 4 kPa in relation to body weight, with lines of best fit and correlation coefficients. ● = Obstetric patients (using post-delivery values); + = non-pregnant patients.

Fig. 2. Inspiratory fresh gas flows required for an end-tidal carbon dioxide tension of 4 kPa in relation to estimated body surface area, with lines of best fit and correlation coefficients. ● = Obstetric patients (using post-delivery values); + = non-pregnant patients.
TABLE II. Fresh gas flow rates required for an end-tidal carbon dioxide of 4 kPa. Mean (SD)

<table>
<thead>
<tr>
<th></th>
<th>Absolute (litre min⁻¹)</th>
<th>Per unit weight (ml kg⁻¹ min⁻¹)</th>
<th>Per unit area (litre m⁻² min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-pregnant (n = 50)</td>
<td>4.88 (0.66)</td>
<td>77.1 (10.6)</td>
<td>2.91 (0.32)</td>
</tr>
<tr>
<td>Pregnant</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before delivery (n = 30)</td>
<td>8.47 (1.35)</td>
<td>121.4 (24.6)</td>
<td>4.86 (0.69)</td>
</tr>
<tr>
<td>After delivery (n = 46)</td>
<td>7.57 (1.00)</td>
<td>109.4 (19.3)</td>
<td>4.39 (0.51)</td>
</tr>
</tbody>
</table>

The difference in FGF requirement in the obstetric patients between those in labour (mean 107 ml kg⁻¹ min⁻¹) and those not in labour (mean 112 ml kg⁻¹ min⁻¹) was not significant (P > 0.2). Figure 3 shows the FGF results (in ml kg⁻¹ min⁻¹) plotted against gestation, there being no significant relationship (r = −0.29).

DISCUSSION

Study design

Our study was meant to provide guidelines for appropriate FGF requirements during a technique of obstetric general anaesthesia, including neuromuscular blockade and artificial ventilation. In the normal clinical circumstances carbon dioxide tensions will not be stable during the induction-to-delivery interval, particularly when the need for delivery is urgent. However, this is the important period during which alteration of the mother’s respiratory indices may influence the condition of the fetus. Extending the induction-to-delivery interval would have enabled more precise estimation of the FGF requirements at this time; however, this would probably be ethically unacceptable, and the results obtained would be less relevant to the clinical circumstances.

Our method of measurement of the FGF rates, involving recording of rotameter settings then

Fig. 3. Inspiratory fresh gas flows required for an end-tidal carbon dioxide tension of 4 kPa in relation to gestation in the obstetric patients, using post-delivery values (r = −0.29).
FGF REQUIREMENTS IN OBSTETRIC ANAESTHESIA

Applying subsequent correction factors, was rather indirect. Ideally, the inspiratory FGF would have been precisely measured at a point near the patient at the time when \( P_{\text{e}CO_2} \) was stable at 4.0 kPa. However, this was found to be unrealistic, for the reasons stated earlier. In practice, the rotameters remained accurate throughout the study and the correction factors were stable on repeated estimation. We feel that any errors in the measurement system are insignificant compared with both the inter-individual variation and the difference between the obstetric and non-obstetric groups.

Arterial to end-tidal \( CO_2 \) gradients

The \( P_{\text{a}CO_2} - P_{\text{e}CO_2} \) gradient in eight obstetric patients was very low, with a mean value of 0.09 kPa. The expected value in non-pregnant anaesthetized patients is of the order of 0.2–0.6 kPa. Situations with increased pulmonary blood flow and ventilation (for example in exercising patients) can produce a negative \( P_{\text{a}CO_2} - P_{\text{e}CO_2} \), gradient [8]; thus these factors may have contributed to the low gradient we found. Since this study was undertaken, another report of \( P_{\text{a}CO_2} - P_{\text{e}CO_2} \) gradients during general anaesthesia for Caesarean section has been published [9]. This showed a mean gradient of 0.004 kPa before delivery (with negative gradients in 43% of the patients), and 0.10 kPa after delivery. Another study [10] showed a mean negative gradient of 0.09 kPa. Thus it would appear that \( P_{\text{e}CO_2} \) is a very good indicator of \( P_{\text{a}CO_2} \) in anaesthetized and ventilated obstetric patients.

Fresh gas flow rates

Our study shows that pregnancy produces a very significant increase in the FGF necessary to produce a carbon dioxide tension of 4.0 kPa during general anaesthesia, with 121 and 109 ml kg\(^{-1}\) min\(^{-1}\) being required in the periods before and after delivery, respectively, representing increases of 57% and 42% over those required in non-pregnant patients. In our study roughly stable pre-delivery results were obtained in 30 patients. In practice the half-time required for \( P_{\text{a}CO_2} \) to stabilize after a change in ventilation is 3–4 min for an increase in ventilation, and 15–20 min for a reduction in ventilation [11]. The induction-to-delivery time in the majority of our patients was between 5 and 10 min, thus attempts to obtain an absolutely steady state before delivery are not realistic. The pre-delivery results, where obtained, were slightly higher than those seen after delivery. Although the metabolic demands of the fetus and placenta cease at delivery, there are additional possible reasons for the higher value before delivery. The transient apnoea at induction, stimulation at intubation, and light level of anaesthesia will all contribute to higher carbon dioxide tensions at the onset of the procedure. We found no significant difference in FGF requirements between patients in labour and those not in labour.

As mentioned earlier, the metabolic and ventilatory changes induced by pregnancy take from 2 to 14 days to resolve post-partum. Thus anaesthesia early in the post-partum period will still require these increased FGF rates.

Other workers who have attempted to determine FGF requirements during obstetric general anaesthesia have divided patients into separate groups allocated to receive different predetermined FGF rates throughout the procedure. Kneeshaw, Harvey and Thomas [12] allocated 26 patients undergoing Caesarean section to groups ventilated with 80, 100, or 120 ml kg\(^{-1}\) min\(^{-1}\) using a Bain breathing system and Penlon Oxford ventilator. They measured \( P_{\text{e}CO_2} \) and claimed that stable values were obtained before delivery in all patients. They did not state how FGF was measured. They found that, with the greatest FGF the mean \( P_{\text{e}CO_2} \) before delivery was 4.2 kPa. Duncan and colleagues [13] allocated 32 patients undergoing Caesarean section to receive FGF of 70 or 100 ml kg\(^{-1}\) min\(^{-1}\), using a Humphrey (ADE) circuit and a Penlon 200 ventilator. They did not state how FGF was estimated, although the tidal volume was recorded with a Wright's respirometer. They found that the mean \( P_{\text{e}CO_2} \) using 100 ml kg\(^{-1}\) min\(^{-1}\) was 4.9 kPa and stated that a flow greater than this would be required to prevent carbon dioxide values increasing above the pre-induction values. They found that, in the group with the lower FGF, the \( P_{\text{e}CO_2} \) had not reached a stable value even by the end of the procedure. Burger and colleagues [10] allocated 18 patients undergoing Caesarean section to receive FGF of 80, 90 or 100 ml kg\(^{-1}\) min\(^{-1}\) using a volume-cycled ventilator, measuring \( P_{\text{a}CO_2} \) and \( P_{\text{e}CO_2} \) and measuring expired gas flow with a Drager Volumeter. They found, using the highest flow rate, that the mean \( P_{\text{a}CO_2} \) at the time of delivery was 4.2 kPa. Thus none of these three groups managed to obtain mean carbon dioxide tensions quite as low as 4.0 kPa, despite using
claimed FGF of 100–120 ml kg\(^{-1}\) min\(^{-1}\). Two of the three did not state how the FGF was measured or estimated, and the third used a Drager Volumeter on the expiratory limb, a method which in our experience gave marked overreading. None used the same measurement system in non-pregnant patients for comparison.

The clinical importance of carbon dioxide tension

Alterations in maternal carbon dioxide tension are important because of their possible effects on fetal wellbeing, rather than effects on the mother. Altering maternal carbon dioxide tensions may affect fetal conditions either by effects on uterine blood flow and gas exchange, or by changes in vascular resistance, acid-base balance and oxygen dissociation in the fetus. In addition, mechanical ventilation may affect uterine blood flow regardless of the maternal carbon dioxide tension. Both induced hypocapnoea (in the hope of reversing fetal acidosis) and induced hypercapnoea (intended to increase fetal blood flow and improve oxygen dissociation) have been recommended in the past.

Much of the work that has shown detrimental effects of hyperventilation has been in anaesthetized animals. A study in guineapigs [14] showed significant worsening of fetal pH with hyperventilation, although these animals were markedly hypotensive. Another often quoted study [15], using sheep, found worsening of fetal pH and oxygen tension during hypocapnoeic hyperventilation, but with normocapnoeic hyperventilation having no effect. A further study in sheep [16] showed that maternal hypocarbia produced higher fetal pH, but decreased fetal oxygen tensions, and showed that mechanical ventilation alone reduced uterine blood flow.

All but one of the clinical studies performed during general anaesthesia for Caesarean section have shown that fetal pH and \(PCO_2\) always change in the same direction as the changes in the mother [10,17–21]. This is despite gross hyperventilation to a maternal \(Pa_{CO_2}\) of less than 2.0 kPa in some of the studies [18,21]. In one study [22] fetal pH did decrease in the group with the most severe maternal hyperventilation, in whom the mean \(Pa_{CO_2}\) was 1.8 kPa, assumedly as a result of reduced fetal perfusion. Studies attempting to determine whether umbilical vein \(PO_2\) is reduced if maternal \(Pa_{CO_2}\) is decreased have given variable results, two showing no relationship [10,21], and two demonstrating a significant relationship [17,20], with one showing no clinical effects [20] and one showing a worse 1-min Apgar score in the neonates from the hyperventilated mothers [17]. Maternal hypercapnoea has been induced in two studies in anaesthetized humans, one showing improvement in umbilical vein oxygen tension but not saturation [23], the other showing increased fetal perfusion, but with very variable effects on fetal acid–base status [24].

Thus all these studies give rather mixed opinions on the ideal maternal \(Pa_{CO_2}\). However, at present, it is increasingly recommended that, during anaesthesia for operative delivery, one should aim to maintain the physiological \(Pa_{CO_2}\) of 4 kPa.

In conclusion, we believe that obstetric general anaesthesia is one of the circumstances in which end-tidal carbon dioxide monitoring is of particular benefit and recommend that, to achieve the normal obstetric carbon dioxide tension of 4 kPa, inspiratory fresh gas flow rates of 109–121 ml kg\(^{-1}\) min\(^{-1}\) be used.

ACKNOWLEDGEMENTS

The authors wish to thank the Trustees of the Elizabeth Garrett Anderson Hospital Appeal Fund who provided the Datex CD102 capnograph used in their hospital for the gynaecological patients, and Vickers Medical Ltd of Basingstoke for the generous loan of an identical capnograph used for the obstetric patients.

REFERENCES

8. Snyder JV, Elliot JL, Grenvik A. Capnography. In:


