ORIGINAL ARTICLE

**Moderate concentrations of supplemental oxygen worsen hypercapnia in obesity hypoventilation syndrome: a randomised crossover study**

Carly Ann Hollier, Alison Rosemary Harmer, Lyndal Jane Maxwell, Collette Menadue, Grant Neville Willson, Gunnar Unger, Daniel Flunt, Deborah Ann Black, Amanda Jane Piper

**ABSTRACT**

**Introduction** In people with obesity hypoventilation syndrome (OHS), breathing 100% oxygen increases carbon dioxide (PCO₂), but its effect on pH is unknown. This study investigated the effects of moderate concentrations of supplemental oxygen on PCO₂, pH, minute ventilation (V̇ₑ) and physiological dead space to tidal volume ratio (V̇ₑ/V̇₉) among people with stable untreated OHS, with comparison to healthy controls. **Methods** In a double-blind randomised crossover study, participants breathed oxygen concentrations (FiO₂) 0.28 and 0.50, each for 20 min, separated by a 45 min washout period. Arterial-venous PCO₂ (PavCO₂) and pH, V̇ₑ and V̇ₑ/V̇₉ were measured at baseline, then every 5 min. Data were analysed using general linear model analysis. **Results** 28 participants were recruited (14 OHS, 14 controls). Among OHS participants (mean±SD arterial PCO₂ 6.7±0.5 kPa; arterial oxygen 8.9±1.4 kPa) FiO₂ 0.28 and 0.50 maintained oxygen saturation 98–100%. After 20 min of FiO₂ 0.28, PavCO₂ change (ΔPavCO₂) was 0.3±0.2 kPa (p=0.013), with minimal change in V̇ₑ and rises in V̇ₑ/V̇₉ of 1±5% (p=0.012). FiO₂ 0.50 increased PavCO₂ by 0.5±0.4 kPa (p=0.012), induced acidaemia and increased V̇ₑ/V̇₉ by 3±3% (p=0.012). V̇ₑ fell by 1.2±2.1 L/min within 5 min then recovered individually to varying degrees. A negative correlation between ΔV̇ₑ and ΔPavCO₂ (r=−0.60, p=0.024) suggested that ventilatory responses were the key determinant of PavCO₂ rises. Among controls, FiO₂ 0.28 and 0.50 did not change PavCO₂ or pH, but FiO₂ 0.50 significantly increased V̇ₑ and V̇ₑ/V̇₉. **Conclusion** Commonly used oxygen concentrations caused hypoventilation, PavCO₂ rises and acidaemia among people with stable OHS. This highlights the potential dangers of this common intervention in this group.

**INTRODUCTION**

In obesity hypoventilation syndrome (OHS), chronic hypercapnia develops as a consequence of obesity. This condition is associated with alveolar hypoventilation, restricted pulmonary function, severe sleep-disordered breathing and higher rates of morbidity, mortality and healthcare costs compared with eucapnic obesity.1–4 OHS affects approximately 0.15–0.3% of the US population5 and over 50% of hospital inpatients with body mass index (BMI) >50 kg/m².1 Despite this, OHS frequently goes undiagnosed among hospital inpatients with obesity.1

Supplemental oxygen is a common medical intervention6 and may be administered to patients with OHS in a range of healthcare settings. British Thoracic Society guidelines on emergency oxygen prescription identify patients with OHS as a group among whom excessive concentrations of supplemental oxygen, causing hyperoxia, could increase carbon dioxide (CO₂) levels and lower pH.6 The basis of the guidelines relies upon expert opinion and data from COPD, because very few studies have investigated the effects of supplemental oxygen in OHS. Among patients with obesity and elevated transcutaneous CO₂ pressure (PCO₂), breathing 100% oxygen induced an average rise in transcutaneous PCO₂ of 0.7 kPa (with rises of >1.3 kPa in three patients).7 However, the effect of oxygen on pH, an important prognostic indicator,2 8 9 was not reported. Furthermore, 100% oxygen is rarely used in clinical practice.2 Hence, the clinical relevance of these data is uncertain.

During acute exacerbations of COPD, hyperoxia arising from supplemental oxygen worsens hypercapnia and pH, and has been linked to more...
frequent admission to intensive care and increased hospital stay of length and mortality.9–11 Hyperoxia-induced hypercapnia in COPD has been attributed to increased ventilation/perfusion (V/Q) inequality, mediated by the reversal of hypoxic vasoconstriction12–14; however recent evidence suggests that hypoventilation may be a quantitatively more important mechanism.15 16 Whether or not these mechanisms apply to OHS, which has a vastly different pathophysiology to COPD, has yet to be determined.

The aims of the present study were to document the time course of changes in PCO2, pH and respiratory variables in response to clinically relevant, moderate concentrations of supplemental oxygen among people with OHS in comparison to a healthy control group; and to examine physiological mechanisms that may explain any oxygen-induced changes in PCO2.

METHODS
Written informed consent was obtained from all participants. The study was approved by the Ethics Committees of Royal Prince Alfred Hospital (protocol no. X12–0067 and HREC/12/RPAH/109) and the University of Sydney (Ref. 14935) and registered on the Australian and New Zealand Clinical Trials Registry (ACTRN1260800172303).

Participants
Patients referred to the Sleep Unit, Royal Prince Alfred Hospital with obesity and possible hypercapnia were screened for eligibility. Inclusion criteria were the combination of obesity (BMI ≥ 30 kg/m2) and daytime hypercapnia (arterial PCO2 (PaCO2) > 6 kPa). Patients were excluded in the case of any other potential cause of hypercapnia, current use of positive airway pressure, acute respiratory/cardiac illness within the previous month, acidemia or psychiatric illness. A control group was recruited concurrently from a sample of convenience. Each control participant was age (±3 years) and gender matched with an OHS participant, non-smoking, with BMI < 30 kg/m2, normal spirometry and no history of cardiorespiratory disease.

Study design and protocol
Using a double-blind randomised crossover design (figure 1), each participant breathed two fractions of inspired oxygen (FiO2 0.28 and 0.50 in random order (sequence 1 or 2), via a breathing circuit, after a circuit acclimatisation period. Each test began with a 10 min period of breathing room air via the circuit (baseline), followed by a 20 min period of supplemental oxygen (FiO2 0.28 or 0.50), and then a 10 min period of breathing room air (recovery). A 45 min washout period separated the two supplemental oxygen tests.

Randomisation of sequence was generated using an online randomisation programme (http://www.randomization.com), with allocation concealed via sealed opaque envelopes. The chief investigator and participants remained blinded throughout. An unblinded co-investigator operated equipment and instructed participants. Testing began between 8:30am and 10:00am. All participants had fasted and abstained from caffeine from midnight.

Instrumentation
The closed breathing circuit comprised a dry rolling-seal spirometer, a bias-flow generator, a soda-lime CO2 absorber and a T-connector at the participant interface. Gas was continuously sampled at the interface using oxygen/CO2 sensors. A stable FiO2 was maintained through titration of bottled air and oxygen using continuous real-time feedback from the oxygen sensor. Immediately after each FiO2 change, the circuit was flushed to allow stabilisation at the new FiO2 within 2 min. Participants breathed through the circuit via a nasal mask (dead space 175 mL) with the mouth closed (n=25), or in the case of nasal obstruction, via a mouthpiece (dead space 100 mL) with a nose peg (n=3).

Outcome measures
On the day of testing, baseline measures of height, weight, spirometry and arterial blood gases (ABGs) were performed.

Arterialised-venous blood was repeatedly sampled to obtain surrogate measures of arterial PCO2 (PavCO2) and pH. We previously described and validated this method in OHS.17 An oximeter continuously measured pulse oxygen saturation (SpO2) (Radical, Masimo, Irvine, California, USA). Signals from the oxygen/CO2 sensors and spirometer were recorded by a computer programme and used to derive and/or display breath-by-breath minute ventilation (V̇E), tidal volume (V̇T) and respiratory rate (RR). Breath-by-breath physiological dead space (V̇Dphys) was calculated using a CO2 expirogram method18 and adjusted by subtracting apparatus dead space, then divided by V̇T to obtain V̇Dphys to V̇T ratio (V̇D/V̇T). Data affected by leak or artefact were systematically excluded. Subsequently, breath-by-breath data were averaged over 60 s.

For final analysis, data obtained during the following periods were included: the final minute of the 10 min baseline, the final minute of each 5 min epoch of supplemental oxygen, and the final minute of the 10 min recovery. Arterialised-venous blood samples were drawn within the last 10 s of each of these periods.

Statistical analysis
Data are presented as mean±SD or median (IQR), and mean difference (MD) and 95% CI for between-group comparisons. A significance level of p<0.05 was used for all comparisons. Between-group MDs in baseline variables were compared using

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Figure 1  Study design. FiO2, inspired oxygen fraction.
independent t-tests. General linear model (univariate, repeated measures) analysis compared responses to supplemental oxygen between participant groups (factor: group; factor interaction: time-by-group) for primary (PavCO₂) and secondary (pH, VE and V D/VT) outcomes; between baseline and supplemental oxygen (factor: time) for primary, secondary and tertiary (VT, RR, VDPhys) outcomes; and between the two oxygen concentrations (factor: concentration) for PavCO₂. For non-parametric data, the Friedman test was used to evaluate effects of time. To account for multiple comparisons the level of significance was adjusted (adj.p) using Holm’s Bonferroni procedure.19 Within the OHS group only, Pearson’s correlation coefficient was calculated to examine potential factors associated with the change in PavCO₂ after 20 min (∆PavCO₂) of FIO₂ 0.50, including baseline PaCO₂, bicarbonate (HCO₃⁻) and arterial oxygen saturation (SaO₂), ∆VE, and ∆V D/VT. The study was powered to detect a ∆PavCO₂ of 0.4 kPa16 from baseline during supplemental oxygen within the OHS group, with an SD estimate of 0.45 kPa (using data from the first five OHS participants), power of 0.8, α of 0.05. A sample of 14 OHS participants (hence 14 matched controls) was required. Data were analysed using PASW 18 (IBM, Armonk, New York, USA).

RESULTS
Fourteen participants with OHS and 14 controls were recruited between August 2008 and February 2012 (figure 2). Baseline characteristics (table 1) show that groups were well matched for age and gender. Participants with OHS presented with superobesity, mild hypercapnia and hypoxaemia, and mild pulmonary restriction.

Table 2 shows all variables at baseline and after 20 min of breathing each oxygen concentration. In both groups, supplemental oxygen induced hyperoxia, with SpO₂ in OHS increasing to 99±1% during FiO₂ 0.28 and 100±0% during FiO₂ 0.50. Figure 3 depicts time courses of PavCO₂, VE and V D/VT. There was no significant effect of test order on PavCO₂ for either group. General linear model comparisons are detailed in table E1, online data supplement.

Between-group comparisons
Responses to supplemental oxygen were significantly different between groups for PavCO₂ and pH (figure 3, table 3), but not for VE after adjustment. There were no significant between-group differences or interaction effects for V D/VT, hence data from both groups were combined to analyse the effects of time for V D/VT.

OHS group: responses to supplemental oxygen
Amongst OHS participants, significant increases in PavCO₂ occurred after 20 min of FiO₂ 0.28 (0.3±0.2 kPa, adj.p=0.013) and FiO₂ 0.50 (0.5±0.4 kPa, adj.p=0.012) (table 2, figure 3). Consequently, proportional changes in pH were observed, resulting in acidemia after 20 min of FiO₂ 0.50 (7.346±0.030, adj.p=0.011). There was a significant difference in PavCO₂ between the two oxygen concentrations, but this became non-significant after adjustment (raw p=0.021, adj.p=0.315).

Table 1 Participant characteristics, baseline arterial blood gases and spirometry

<table>
<thead>
<tr>
<th>OHS</th>
<th>Controls</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>48±12</td>
<td>48±12</td>
</tr>
<tr>
<td>Gender (F/M)</td>
<td>3/11</td>
<td>3/11</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>53±7</td>
<td>25±4</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>154±21</td>
<td>73±15</td>
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<tr>
<td>pH</td>
<td>7.395±0.030</td>
<td>7.414±0.019*</td>
</tr>
<tr>
<td>PaCO₂ (kPa)</td>
<td>6.7±0.5</td>
<td>5.5±0.4*</td>
</tr>
<tr>
<td>PaO₂ (kPa)</td>
<td>8.9±1.4</td>
<td>14.3±1.1*</td>
</tr>
<tr>
<td>SaO₂ (%)</td>
<td>92±3</td>
<td>98±1*</td>
</tr>
<tr>
<td>HCO₃⁻ (mmol/L)</td>
<td>30.3±1.7</td>
<td>25.8±1.2*</td>
</tr>
<tr>
<td>a-aDO₂ (kPa)</td>
<td>3.6±1.4</td>
<td>0.9±1.2*</td>
</tr>
<tr>
<td>Haemoglobin (g/L)</td>
<td>153±20</td>
<td>143±11</td>
</tr>
<tr>
<td>FEV₁ (L)</td>
<td>2.39±0.72</td>
<td>3.71±0.71</td>
</tr>
<tr>
<td>FEV₁% predicted</td>
<td>73±14</td>
<td>106±11</td>
</tr>
<tr>
<td>FVC (L)</td>
<td>3.03±0.85</td>
<td>4.5±0.77</td>
</tr>
<tr>
<td>FVC% predicted</td>
<td>77±14</td>
<td>107±13</td>
</tr>
<tr>
<td>FEV₁FVC (%)</td>
<td>79±6</td>
<td>82±5</td>
</tr>
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</table>

Data presented as mean±SD; p value represents two-tailed significance from independent t-tests comparing control and OHS groups.

*Data reported from n=13, as arterial blood gas could not be performed in one control participant.

A-aDO₂, alveolar-arterial oxygen difference; BMI, body mass index; FEV₁, forced expired volume in 1 s; FVC, forced vital capacity; HCO₃⁻, bicarbonate; OHS, obesity hypoventilation syndrome; PaCO₂, arterial partial pressure of CO₂; PaO₂, arterial partial pressure of O₂.
Table 2  Physiological variables at baseline and at the end of FIO2 0.28 and FIO2 0.50 tests

<table>
<thead>
<tr>
<th></th>
<th>FIO2 0.28</th>
<th></th>
<th>Adj. p value</th>
<th>FIO2 0.50</th>
<th></th>
<th>Adj. p value</th>
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<tr>
<td></td>
<td>Room air baseline</td>
<td>20 min</td>
<td></td>
<td>Room air baseline</td>
<td>20 min</td>
<td></td>
</tr>
<tr>
<td>OHS group</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SpO2 (%)</td>
<td>94±3</td>
<td>99±1</td>
<td>–</td>
<td>94±3</td>
<td>100±0</td>
<td>–</td>
</tr>
<tr>
<td>PavCO2 (kPa)</td>
<td>7.1±0.6</td>
<td>7.4±0.6</td>
<td>0.013</td>
<td>7.2±0.6</td>
<td>7.7±1.0</td>
<td>0.012</td>
</tr>
<tr>
<td>pH</td>
<td>7.37±0.019</td>
<td>7.359±0.027</td>
<td>0.406*</td>
<td>7.373±0.021</td>
<td>7.346±0.030</td>
<td>0.011</td>
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<tr>
<td>VE (L/min)</td>
<td>9.9±2.3</td>
<td>9.9±2.8</td>
<td>0.997</td>
<td>9.6±2.1</td>
<td>9.3±2.9</td>
<td>0.224*</td>
</tr>
<tr>
<td>VD/VT (ratio)</td>
<td>0.28±0.05</td>
<td>0.29±0.03</td>
<td>0.012</td>
<td>0.29±0.05</td>
<td>0.32±0.05</td>
<td>0.012</td>
</tr>
<tr>
<td>VDphys (mL)</td>
<td>200±55</td>
<td>196±26</td>
<td>&gt;0.999</td>
<td>194±56</td>
<td>192±37</td>
<td>&gt;0.999</td>
</tr>
<tr>
<td>Vt (mL)</td>
<td>633±149</td>
<td>597±129</td>
<td>0.012</td>
<td>578±105</td>
<td>489±107</td>
<td>0.012</td>
</tr>
<tr>
<td>RR (br/min)</td>
<td>17.5±5.2</td>
<td>18.2±4.7</td>
<td>&gt;0.999</td>
<td>18.1±4.9</td>
<td>18.1±4.2</td>
<td>&gt;0.999</td>
</tr>
<tr>
<td>Control group</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SpO2 (%)</td>
<td>98±1</td>
<td>100±1</td>
<td>–</td>
<td>98±1</td>
<td>100±0</td>
<td>–</td>
</tr>
<tr>
<td>PavCO2 (kPa)</td>
<td>5.5±0.4</td>
<td>5.6±0.2</td>
<td>0.726</td>
<td>5.4±0.3</td>
<td>5.4±0.4</td>
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<tr>
<td>pH</td>
<td>7.408±0.023</td>
<td>7.397±0.010</td>
<td>&gt;0.999</td>
<td>7.407±0.020</td>
<td>7.407±0.023</td>
<td>&gt;0.999</td>
</tr>
<tr>
<td>VE (L/min)</td>
<td>7.5±1.6</td>
<td>7.5±1.7</td>
<td>&gt;0.999</td>
<td>7.6±1.8</td>
<td>8.6±1.9</td>
<td>0.019</td>
</tr>
<tr>
<td>VD/VT (ratio)</td>
<td>0.27±0.05</td>
<td>0.29±0.04</td>
<td>0.012</td>
<td>0.28±0.04</td>
<td>0.32±0.04</td>
<td>0.012</td>
</tr>
<tr>
<td>VDphys (mL)</td>
<td>232±79</td>
<td>237±53</td>
<td>0.085*</td>
<td>244±123</td>
<td>263±97</td>
<td>0.085*</td>
</tr>
<tr>
<td>Vt (mL)</td>
<td>813 (353)</td>
<td>754 (356)</td>
<td>&gt;0.999</td>
<td>751 (285)</td>
<td>751 (264)</td>
<td>&gt;0.999</td>
</tr>
<tr>
<td>RR (br/min)</td>
<td>10.3±4.2</td>
<td>10.5±4.5</td>
<td>0.195*</td>
<td>10.6±3.7</td>
<td>11.8±3.6</td>
<td>0.195*</td>
</tr>
</tbody>
</table>

*Data presented as mean±SD or median (IQR).
Adj. p value: significance level from general linear model analysis, change over time (ie room air vs oxygen) after Holm’s Bonferroni correction (refer to table E1, online supplement for full details).
*Raw p value significant but adj. p value=non-significant.
FIO2, inspired oxygen fraction; PavCO2, arterialised-venous carbon dioxide; RR, respiratory rate; SpO2, pulse oxygen saturation; VD/VT, physiological dead space to tidal volume ratio; VDphys, physiological dead space; VE, minute ventilation; VT, tidal volume.

Figure 3  Time course of changes in PavCO2, VE and VD/VT during air/oxygen breathing tests for OHS group (open circles) and control group (closed circles), with results of general linear model analysis of between-group differences (factor: group, and group by time). tAdjusted p value=0.01; FIO2, inspired oxygen fraction; NS, non-significant; OHS, obesity hypoventilation syndrome; PavCO2, arterialised-venous CO2; VE, minute ventilation; VD/VT, dead space to tidal volume ratio.

There was a positive correlation between $\Delta P_{avCO_2}$ (FiO$_2$ 0.50) and $P_{aCO_2}$ ($r=0.60$, $p=0.023$) and $HCO_3^-$ ($r=0.58$, $p=0.030$), but not $SaO_2$ ($r=-0.48$, $p=0.08$). Furthermore, a negative correlation between $\Delta P_{avCO_2}$ and $\Delta VE$ was found ($r=-0.60$, $p=0.024$), but not $\Delta V_T/V_T$ ($r=0.42$, $p=0.18$).

There was no significant change in $VE$ when breathing FiO$_2$ 0.28 (table 2). In contrast, during FiO$_2$ 0.50 a consistent fall in $VE$ of 1.2±2.1 L/min (12±22%) below baseline occurred within 5 min (figure 3). Thereafter, a varying recovery in $VE$ was observed (figure 4C), such that after 20 min $VE$ remained below baseline in six participants and exceeded baseline $VE$ by >5% in four participants. After 20 min, group mean $VE$ was 3±20% below baseline, which became non-significant after adjustment (raw $p=0.014$, adj.$p=0.224$). Decreases in $VE$ were attributable to significant falls in $V_T$, as RR was unchanged.

During FiO$_2$ 0.28 and 0.50, $V_T/V_T$ increased by 1±5% and 3±3%, respectively (adj.$p=0.012$), in the absence of significant changes in $V_{Dphys}$.

**Control group: responses to supplemental oxygen**

Among the controls, there were no significant changes in $P_{avCO_2}$ or pH during either FiO$_2$ (table 2, figure 3), and no significant differences for $P_{avCO_2}$ between concentrations. During FiO$_2$ 0.28 there were no significant changes in $VE$, $V_T$ or RR. However, breathing FiO$_2$ 0.50 increased $VE$ by 15±11% after 20 min (adj.$p=0.019$), due to a slight, non-significant increase in RR (raw $p=0.01$, adj.$p=0.170$).

Significant increases in $V_T/V_T$ of 1±3% and 4±3% were observed during FiO$_2$ 0.28 and 0.50 respectively (adj.$p=0.012$). This was accompanied by small rises in $V_{Dphys}$ which became non-significant after adjustment (raw $p<0.001$, adj.$p=0.085$).

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**Table 3**  
<table>
<thead>
<tr>
<th></th>
<th>MD ($\Delta$ at 20 min)*</th>
<th>95% CI</th>
<th>Raw p value</th>
<th>Adj. p value</th>
<th>Raw p value</th>
<th>Adj. p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{avCO_2}$ (kPa)</td>
<td>0.31</td>
<td>0.13 to 0.49</td>
<td>&lt;0.001</td>
<td>0.010</td>
<td>&lt;0.001</td>
<td>0.014</td>
</tr>
<tr>
<td>pH</td>
<td>−0.014</td>
<td>−0.023 to −0.005</td>
<td>&lt;0.001</td>
<td>0.011</td>
<td>0.001</td>
<td>0.019</td>
</tr>
<tr>
<td>$VE$ (L/min)</td>
<td>−0.8</td>
<td>−1.3 to −0.38</td>
<td>0.045</td>
<td>0.585</td>
<td>0.051</td>
<td>0.612</td>
</tr>
<tr>
<td>$V_T/V_T$ (ratio)</td>
<td>0.01</td>
<td>−0.03 to 0.01</td>
<td>0.085</td>
<td>0.850</td>
<td>0.128</td>
<td>&gt;0.999</td>
</tr>
</tbody>
</table>

Adj. p value: significance level from general linear model analysis, OHS versus controls, after Holm’s Bonferroni correction.  
*MD: mean difference (OHS-control) for $\Delta$ values at 20 min.  
OHS, obesity hypoventilation syndrome; $P_{avCO_2}$, arterialised-venous carbon dioxide; $V_T$, physiological dead space to tidal volume ratio; $V_{Dphys}$, physiological dead space; $VE$, minute ventilation.

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**Figure 4**  
Individual and group responses to supplemental oxygen concentration (FiO$_2$) 0.28 and 0.50 for OHS group (A and C) and control group (A and D), showing change in arterialised-venous carbon dioxide from room air baseline ($\Delta P_{avCO_2}$) (A and B), and change in minute ventilation from room air baseline ($\Delta VE$) (C and D). Each figure includes individual changes at 20 min for FiO$_2$ 0.28 and group mean±SD on the left, and individual changes at 20 min for FiO$_2$ 0.50 and group mean±SD on the right. OHS, obesity hypoventilation syndrome.
DISCUSSION
To our knowledge, this is the first study to investigate the effects of clinically relevant, moderate concentrations of supplemental oxygen on PCO2 and pH, V̇D/V̇T and V̇E and its determinants among people with OHS. In OHS, hyperoxia induced by breathing ḞO₂ 0.28 and ḞO₂ 0.50 caused significant rises in PavCO₂. Accordingly, pH decreased, resulting in acidemia during ḞO₂ 0.50. Breathing ḞO₂ 0.50 was accompanied by hypoventilation and increases in V̇D/V̇T. However, changes in V̇E were the key determinant of PavCO₂ rises. Breathing ḞO₂ 0.50 also increased V̇I/V̇E in the control group, but controls maintained a stable PavCO₂ and pH through a 15% increase in V̇E. The findings of the present study bring into question the safety of moderate concentrations of supplemental oxygen among patients with untreated OHS and provide evidence to substantiate current clinical guidelines on oxygen prescription.

Among participants with OHS, hyperoxia induced by supplemental oxygen significantly worsened hypercapnia and lowered pH. In an earlier study, breathing 100% oxygen increased transcutaneous PCO₂ in obesity-associated hypercapnia, but the clinical relevance of this report was unclear because pH was not measured and transcutaneous PCO₂ was used, inherently adding potential errors to PCO₂ measures and preventing a definitive diagnosis of OHS. The present study provided further physiological detail and insight into the clinical relevance of the effects of hyperoxia in OHS. Although the minimal important difference for PCO₂ in OHS has not been defined, in the present study the rise in PavCO₂ during ḞO₂ 0.50 (0.5±0.4 kPa) was considered clinically significant because it induced acidemia. In patients with COPD, hyperoxia-related acidemia is associated with higher in-hospital morbidity, and this may apply to acutely unwell patients with OHS but has not been addressed. Therefore, in light of the results of the present study, the influence of supplemental oxygen usage on morbidity, mortality and healthcare utilisation in people with OHS requires investigation.

Ventilatory responses to hyperoxia
Controls
Interestingly, V̇D/V̇T increased among the control group with both oxygen concentrations, with rises of the same magnitude as those of the OHS group (figure 3). Despite this, PavCO₂ and pH remained relatively stable, albeit with some individual variation (figure 4B). During ḞO₂ 0.50, stable PavCO₂ levels were achieved by a 15±11% increase in V̇E. This is consistent with previous observations among healthy controls breathing 100% O₂ and is indicative of normal ventilatory control. Hyperoxic hyperventilation in healthy individuals is usually preceded by a fall in V̇E (∼5–12%) within the first 30 s to 2 min of breathing 100% oxygen via inhibition of the peripheral chemoreceptors, which are tonically active within a normal PaO₂ range. However, the washout time of circuit gases prevented this being captured in the present study. Quickly thereafter, V̇E increases above baseline due to transient increases in PaCO₂ from initial hyperventilation, the Haldane effect, increases in V̇I/V̇E and possibly in part through direct stimulation of chemoreceptors.

Obesity hypoventilation syndrome
Participants with OHS also experienced increases in V̇D/V̇T during hyperoxia. However, unlike the controls, breathing ḞO₂ 0.50 was invariably characterised by marked hyperventilation for the first 5–10 min, followed by a partial recovery in V̇E. The recovery of V̇E was usually insufficient to overcome the increase in V̇I/V̇E hence PavCO₂ was elevated after 20 min of ḞO₂ 0.50 in most participants (figure 4). There was a negative correlation between ΔV̇E and ΔPavCO₂, but ΔV̇D/V̇T was not associated with ΔPavCO₂. These results suggest that the PavCO₂ rises observed amongst OHS participants were largely a result of inadequate ventilatory control. Impaired respiratory chemosensitivity is a common feature of OHS and may explain why the initial decrease in V̇E during hyperoxia was of a larger magnitude, with much slower recovery, than that reported in controls. Blunted hypercapnic ventilatory responses could also explain why an elevation of PavCO₂ at 20 min was tolerated by most participants. However, hypercapnic ventilatory responses are highly variable between individuals with OHS and are sometimes within the normal range in patients with mild hypercapnia, which may explain the variability in ventilatory responses to hyperoxia in the OHS group. We did not test ventilatory responses and are therefore unable to confirm their role in the changes in PavCO₂ observed during hyperoxia.

Factors potentially influencing V̇D/V̇T in controls and OHS
In both groups, V̇D/V̇T increased significantly during hyperoxia, although the contribution of this small change towards potential PavCO₂ rises is uncertain. Increased V̇D/V̇T could arise from an increase in V̇Dphys, a decrease in V̇T or both. In studies measuring V/Q distributions in healthy controls, and patients with OHS, breathing 100% oxygen has been shown to increase perfusion to poorly ventilated regions of lung through the release of local hypoxic vasconstriction. This result in underperfusion of well ventilated regions, thereby increasing V̇Dphys. This mechanism is plausible among the control group, in whom a small increase in V̇Dphys was observed during ḞO₂ 0.50. However, this change became non-significant after statistical adjustment. In contrast, no change was observed in V̇Dphys among the OHS group. It has been shown that V̇Dphys has a proportional relationship with V̇E and therefore was unable to characterise the complex interactions between pulmonary ventilation and perfusion, gas exchange and breathing pattern when patients were breathing moderate oxygen concentrations.

Clinical implications
Clinically important differences between the two concentrations of oxygen were observed in the present study, that is, hyperoxia induced by ḞO₂ 0.28 caused minimal changes in pH or V̇E, while ḞO₂ 0.50 caused hypoventilation and acidemia. Furthermore, compared with responses to ḞO₂ 0.50 in our OHS participants, even more marked changes in PCO₂ and V̇E occurred during 100% oxygen in obesity-associated hypercapnia. The mechanisms by which hyperoxia induces hypoventilation in OHS remain unclear. However, these findings suggest that a greater degree of respiratory depression occurs with higher oxygen concentrations. Therefore, in stable OHS, hyperoxia caused by breathing ḞO₂ 0.28 may be less harmful than ḞO₂ 0.50 or 1.0.

Substantial inter-individual variability in ΔPavCO₂ during hyperoxia was evident among the OHS group; as has been reported in obesity-associated hypercapnia and COPD.
Therefore it would be clinically useful to identify features that may predict adverse responses to hyperoxia. Strong associations between ΔPavCO2 and baseline PaCO2 and HCO3− were observed, suggesting that patients with OHS and severe hypercapnia (and associated elevated HCO3− levels) are more likely to develop worsening hypercapnia during hyperoxia. This is plausible, given the tendency for people with OHS and a higher PaCO2 to have lower hypercapnic ventilatory responses than those with lower PaCO2.24–26 Elevated HCO3− may also directly blunt hypercapnic ventilatory responses in OHS, through an increased acid-buffering capacity.31 32 Previous data also suggest that people with more severe hypoxaemia may experience larger PCO2 rises during hyperoxia,7 although this was not evident amongst our mildly hypoxaemic group.

Participants in the present study were clinically stable, with mild hypercapnia and hypoxaemia. Therefore our findings probably underestimate the dangers of hyperoxia in people with OHS with severe hypercapnia and/or acute cardiorespiratory illness. The effects of supplemental oxygen in this population warrant further investigation. Even so, the findings of the present study highlight the potential risks associated with the administration of moderate concentrations of supplemental oxygen among people with OHS. These findings also provide an evidence base for current guidelines,6 which recommend that people with more severe hypoxaemia may experience larger PCO2 rises during hyperoxia,7 although this was not evident amongst our mildly hypoxaemic group.

In this study, we documented acute responses to breathing supplemental oxygen for 20 min. Based on the time course of PavCO2 (figure 3), a plateau in PavCO2 occurred after 10 min of breathing oxygen. However, due to the large capacity of the body for CO2 storage, CO2 equilibrium is not usually achieved until 20–30 min after a change in ventilation33 and therefore participants may not have reached CO2 steady state. In clinical practice, patients are usually treated with supplemental oxygen for extended periods. Hence, the effects of longer periods of supplemental oxygen require evaluation to further strengthen clinical practice guidelines.

CONCLUSION

Among people with mild, stable untreated OHS, breathing moderate concentrations of supplemental oxygen increased PavCO2, sufficient to induce acidemia during FIO2 0.50. These findings highlight the need for caution during supplemental oxygen administration among people with OHS and support current clinical guidelines which recommend targeting an SpO2 88–92%, thereby avoiding hyperoxia and hypoxaemia. Oxygen supplementation should also include close monitoring and periodic reassessment of ABGs.6

Limitations

In this study, we documented acute responses to breathing supplemental oxygen for 20 min. Based on the time course of PavCO2 (figure 3), a plateau in PavCO2 occurred after 10 min of breathing oxygen. However, due to the large capacity of the body for CO2 storage, CO2 equilibrium is not usually achieved until 20–30 min after a change in ventilation33 and therefore participants may not have reached CO2 steady state. In clinical practice, patients are usually treated with supplemental oxygen for extended periods. Hence, the effects of longer periods of supplemental oxygen require evaluation to further strengthen clinical practice guidelines.

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Contributors

CAH: contributed to design and implementation of the study, data collection, statistical analysis, preparation and editing of manuscript; ARH, UIM, CM: contributed to design and implementation of the study, data collection, and editing of manuscript; GWN: contributed to original concept and design of the study, and editing of manuscript; GIU: designed and built breathing circuit and data acquisition/analysis programmes, and contributed to study design, data analysis and editing of manuscript; DF: contributed to design and implementation of study, data collection and editing of the manuscript; DAB: contributed to design of the study, and editing of manuscript; AJP: contributed to design and implementation of the study, and editing of manuscript.

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Competing interests

AIP received fees for lectures from ResMed, Asia Pacific and Phillips Respironics, Australia. She has also received a grant to evaluate therapy in obesity hyperventilation syndrome from the ResMed Foundation. GNW has previously been a consultant to ResMed, Asia Pacific. He has received fees for lectures from ResMed, Asia Pacific. All other authors have no actual or potential competing interests to disclose.

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Carly Ann Hollier, Alison Rosemary Harmer, Lyndal Jane Maxwell, Collette Menadue, Grant Neville Willson, Gunnar Unger, Daniel Flunt, Deborah Ann Black and Amanda Jane Piper

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