A STUDY OF HUMIDIFICATION IN TRACHEOSTOMIZED DOGS

HIROSHI NOGUCHI, YOSHIAKI TAKUMI AND OSAMU AOCHI

SUMMARY

In order to determine the optimal conditions for humidification of inspired air through a tracheostomy, tracheostomized dogs were allowed to breathe humidified air, the temperature of which was deliberately varied between 15°C and 40°C. At 15°C, the air was saturated lower than 40% but was fully saturated at the other temperatures. Measurements of alveolar ventilation, functional residual capacity, lung compliance, alveolar/arterial Po2 difference, pulmonary shunt ratio, cardiac output and oxygen consumption suggest that satisfactory conditions of lung function obtained when the animals breathed fully saturated air administered at a temperature between 20°C and 30°C.

Inspirated gas humidification is considered to be important in the long-term management of patients breathing through an endotracheal tube or tracheostomy (Burton, 1962; Spalding and Crampton Smith, 1963). Little is known about the effect of humidification on the lung functions because much of our previous knowledge has been derived from autopsy findings. It is difficult to separate the effects of poor humidification from other factors such as oxygen toxicity, infection and retention of secretions. The purpose of this study is to find out the conditions of humidification which are least damaging to the lungs of tracheostomized dogs.

MATERIALS AND METHODS

Thirty adult mongrel dogs (weight range 7-15 kg) were anaesthetized by intravenous injection of pentobarbitone 15-20 mg/kg and secured in the supine position. A catheter (gauge 5) was advanced from the femoral vein to the right ventricle under fluoroscopy and was used for sampling mixed venous blood and for administering lactated Ringer solution 100 ml/kg/24 hr. Arterial blood was sampled from a catheter in the femoral artery. The tracheostomy was performed and a cuffed tube inserted in the trachea. The cuff was inflated tightly during the experiment. Functional residual capacity (FRC) was measured using the closed circuit helium dilution method (Bartels, 1963). Thereafter, suxamethonium 1.5 mg/kg was given and the lung and chest wall compliance was measured using the method of Sato (1970). Ventilation was thereafter controlled using an AIKA model R-50 volume preset ventilator (Ichikawa, Tokyo). The ventilator frequency was set at 20 b.p.m. and the tidal volume adjusted to provide a minute volume of about 300 ml/kg. After 30 minutes of artificial ventilation, end-tidal and mixed expired gas and arterial and mixed venous blood were sampled. The respiratory minute volume was measured with a Wright respirometer in the expiratory limb of the ventilator circuit. Oesophageal and room temperatures were noted.

The dogs usually recovered from the effects of suxamethonium at about 30 minutes and thereafter breathed air from a T-piece, into one limb of which air flowed from a compressor at a rate of 40 l./min. This gas passed through either a canister of CaCl2 (to ensure complete drying) or a home-made humidifier. The humidifier used (fig. 1), is a closed metallic water container (30×30×50 cm), at the bottom of which a bubbling head (a quadrate box 20×20×2 cm with numerous pin-holes on its upper surface) is built and the air from compressor was delivered into this head. Water in the humidifier was heated with an electric heating element placed just over the bubbling head. This heater was regulated by a thermostat placed about 30 cm upstream from the T-piece.

The dogs were divided into six groups. Group I inhaled dried air for 6 hours. The other groups breathed humidified air for 24 hours. Humidification was achieved by the humidifier mentioned above and the thermostat setting was as follows: Group II, 20°C (4 dogs); Group III, 25°C (4 dogs); Group IV, 30°C (4 dogs); Group V, 35°C (5 dogs); Group VI, 40°C (5 dogs).

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FIG. 1. Method of humidification. Dogs were connected with the T-piece most downstream in the circuit. The humidifier was of the bubble type and the water temperature in it was regulated by the thermostat placed about 30 cm upstream from the T-piece. About 40 l/min of compressed air was blown into the humidifier in order to prevent breathing ambient air from the open limb of the T-piece.

The fluctuation in temperature was ±3°C around the preset value. The humidity of the inspired air was determined at the entrance to the T-piece by means of hygrometry (Aochi, Kawaguchi and Fugita, 1963). The gas was found to be under 40% saturated at 15°C (Group I) but 99–100% saturated in the other five groups. At the end of 6 hours (Group I) or 24 hours (Groups II–VI) of spontaneous breathing, measurements of FRC and static lung compliance and sampling of blood and air were repeated as before.

\( \text{Po}_2, \text{Pco}_2 \) and pH in blood samples were determined using the appropriate Radiometer electrodes. The temperature of electrodes was adjusted to equal that of the oesophageal temperature of the dog. Oxygen and carbon dioxide contents of blood were determined using the method of Van Slyke and Neil (1924). Fractional concentration of oxygen and carbon dioxide in end-tidal and mixed expired air were determined using the Scholander micrometric apparatus (1947).

**Calculations** (Comroe et al., 1962).

1. Oxygen consumption (\( \dot{V}_{O_2} \)):
   \[
   \dot{V}_{O_2} = \left( F_{O_2} - \frac{1 - F_{CO_2} - F_{CO_2}}{1 - F_{O_2} - F_{CO_2}} \right) \times k_1 \times V_E
   \]

2. Carbon dioxide output (\( \dot{V}_{CO_2} \)):
   \[
   \dot{V}_{CO_2} = k_1 \times V_E \times (F_{CO_2} - F_{CO_2})
   \]

3. Alveolar ventilation volume (\( V_A \)):
   \[
   V_A = k_2 \times f \times (V_T - V_D_{ANAT})
   \]

4. Physiological deadspace (\( V_D_{PHTS} \)):
   \[
   V_D_{PHTS} / V_T = (P_{CO_2} - P_{CO_2}) / P_{CO_2}
   \]

5. Anatomical deadspace (\( V_D_{ANAT} \)):
   \[
   V_D_{ANAT} / V_T = (F_{CO_2} - F_{CO_2}) / F_{CO_2}
   \]

6. Cardiac output (\( Q_T \)):
   \[
   Q_T = \dot{V}_{O_2} / (C_{O_2} - C_{O_2})
   \]

7. Alveolar/arterial \( \text{Po}_2 \) difference ((A-a)\( \text{Po}_2 \) diff)
   \[
   (A-a) \text{Po}_2 \text{ diff} = P_{A_2} - P_{A_2}
   \]

Mean alveolar \( \text{Po}_2 \) (\( P_{A_2} \)) was derived by "alveolar air equation" (Riley et al., 1946; Fenn, Rahn and Otis, 1946) on the assumption that the dog was in a new steady state after the mechanical ventilation for 30 minutes. Therefore,

\[
P_{A_2} = P_{O_2} - P_{O_2} / R \ldots R = \dot{V}_{CO_2} / \dot{V}_{O_2}
\]

8. Pulmonary physiological shunt ratio (\( Q_S / Q_T \))
   \[
   Q_S / Q_T = (C_{O_2} - C_{O_2}) / (C_{O_2} - C_{O_2})
   \]
Pulmonary capillary oxygen content (Cc'o²) was calculated with the next equation,

\[
\text{(9) Blood oxygen content (vol%)} = [1.34 \times (\% \text{ saturation}/100) \times \text{Hb(g)}] + (0.003 \times \text{Po}_2)
\]

Oxygen saturation in the pulmonary capillary blood was derived from arterial pH and base excess and the calculated \(\text{Pa}_o\) (equation 7) with the aid of the "blood-gas calculator" (Severinghaus, 1966). Hb content in the arterial blood was obtained by substituting the measured oxygen content, \(\text{Po}_2\) and the calculated oxygen saturation in the arterial blood into the equation 9. \(\text{Fi}_o\) and \(\text{Fi}_c\) were found to be 0.2082 and 0.0005.

**RESULTS**

The changes in the measured and calculated values are summarized in table I.

In all groups, \(\text{Pa}_o\) fell during the experiment. A statistically significant fall occurred in Groups I and

\(k_1\): factor for conversion from ATPS to STPD.

\(k_2\): factor for conversion from ATPS to BTPS.

\(R\): respiratory quotient.

\(VE\): expiratory minute volume.

\(VT\): tidal volume.

\(f\): respiratory frequency.

\(F\text{ACO}_2\): carbon dioxide concentration in end-tidal air.

\(F\text{I}_o\) and \(F\text{I}_c\): oxygen and carbon dioxide concentration in inspired air.

\(F\text{EO}_2\) and \(F\text{EO}_c\): oxygen and carbon dioxide concentration in mixed expired air.

\(\text{Pa}_o\) and \(\text{Pa}_c\): arterial \(\text{Po}_2\) and \(\text{Pc}_c\).

\(\text{Cao}_2\) and \(\text{Cvo}_3\): oxygen content in arterial and mixed venous blood.

\(P\text{I}_o\) and \(P\text{I}_c\): \(\text{Po}_2\) in inspired air and \(\text{Pc}_c\) in mixed expired air.

**TABLE I. Changes in measured and calculated lung function values during the experiment (X±SX).**

<table>
<thead>
<tr>
<th></th>
<th>Group I</th>
<th>Group II</th>
<th>Group III</th>
<th>Group IV</th>
<th>Group V</th>
<th>Group VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n)</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Duration (hr)</td>
<td>&lt;40</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Humidification (%)</td>
<td>100% at 15°C</td>
<td>100% at 20°C</td>
<td>100% at 25°C</td>
<td>100% at 30°C</td>
<td>100% at 35°C</td>
<td>100% at 40°C</td>
</tr>
<tr>
<td>(\Delta VE) (ml/kg/min)</td>
<td>-1.4 ± 2.8</td>
<td>-1.5 ± 10.9</td>
<td>-4.3 ± 4.2</td>
<td>-5.5 ± 3.4</td>
<td>-3.8 ± 5.9</td>
<td>-2.2 ± 4.8</td>
</tr>
<tr>
<td>(\Delta V_A) (ml/kg/min)</td>
<td>+1.5 ± 9.9</td>
<td>+13.3 ± 10</td>
<td>+11.5 ± 33.3</td>
<td>-5.3 ± 6.6</td>
<td>-1.6 ± 10.9</td>
<td>+15.4 ± 23.1</td>
</tr>
<tr>
<td>(\Delta P_{a_o}) (mm Hg)</td>
<td>-13.3 ± 3.3***</td>
<td>-11.5 ± 4.8*</td>
<td>-8.1 ± 6.5</td>
<td>-6.5 ± 2.5*</td>
<td>-5.8 ± 4.9</td>
<td>-19.0 ± 4.3***</td>
</tr>
<tr>
<td>(\Delta P_{a_c}) (mm Hg)</td>
<td>-4.0 ± 2.6</td>
<td>-3.3 ± 4.9</td>
<td>+0.3 ± 0.8</td>
<td>-3.4 ± 3.0</td>
<td>+2.7 ± 1.8</td>
<td>+10.4 ± 4.7</td>
</tr>
<tr>
<td>(\Delta P_{D_{H_{2}O}}) (mm Hg)</td>
<td>-5.0 ± 5.5</td>
<td>-0.3 ± 3.5</td>
<td>+8.0 ± 4.2</td>
<td>+1.2 ± 5.6</td>
<td>+5.9 ± 4.8</td>
<td>+7.5 ± 6.0</td>
</tr>
<tr>
<td>(\Delta V_{D_{N_{2}}}/VE) (%)</td>
<td>-1.1 ± 3.2</td>
<td>-6.0 ± 3.1</td>
<td>-3.1 ± 3.5</td>
<td>+2.2 ± 4.3</td>
<td>-0.7 ± 2.6</td>
<td>-6.9 ± 4.6</td>
</tr>
<tr>
<td>(\Delta Qt) (ml/min)</td>
<td>-28 ± 26</td>
<td>+48 ± 35</td>
<td>+38 ± 35</td>
<td>+42 ± 25</td>
<td>+74 ± 33</td>
<td>-8.3 ± 31</td>
</tr>
<tr>
<td>(\Delta (A-a) P_{o_2}) diff (mm Hg)</td>
<td>+15.9 ± 5.6**</td>
<td>+8.3 ± 6.1</td>
<td>-6.4 ± 8.4</td>
<td>+5.0 ± 5.1</td>
<td>-4.0 ± 3.7</td>
<td>+12.8 ± 6.3</td>
</tr>
<tr>
<td>(\Delta Q_{O_2}) (%)</td>
<td>+4.2 ± 1.1**</td>
<td>+5.2 ± 1.8*</td>
<td>+5.2 ± 1.8*</td>
<td>+8.3 ± 5.1</td>
<td>+3.8 ± 2.7</td>
<td>+6.6 ± 2.5**</td>
</tr>
<tr>
<td>(\Delta V_{o_2}) (ml/kg/min)</td>
<td>+1.1 ± 0.6</td>
<td>+0.6 ± 0.4</td>
<td>-0.8 ± 0.3*</td>
<td>+1.0 ± 0.5</td>
<td>+0.5 ± 0.8</td>
<td>+1.0 ± 0.5</td>
</tr>
<tr>
<td>(\Delta C_{1}) (ml/kg/min)</td>
<td>-0.4 ± 0.7</td>
<td>-1.4 ± 1.0</td>
<td>-1.1 ± 0.4*</td>
<td>-2.3 ± 1.3</td>
<td>-0.1 ± 0.2</td>
<td>-0.6 ± 1.4</td>
</tr>
<tr>
<td>(\Delta F_{R_{C}})</td>
<td>-27 ± 3***</td>
<td>-11 ± 5</td>
<td>-2.5 ± 18</td>
<td>+5 ± 6</td>
<td>-12 ± 2***</td>
<td>-14 ± 2.3***</td>
</tr>
<tr>
<td>(\Delta Compliance)</td>
<td>-27 ± 4***</td>
<td>-2.5 ± 3.2</td>
<td>+5.0 ± 1.0*</td>
<td>+6.0 ± 7.3</td>
<td>-7.2 ± 2.3***</td>
<td>-13.0 ± 4.4**</td>
</tr>
</tbody>
</table>

† Mean value in the first and second determinations.

* 0.1 > P  ** 0.05 > P  *** 0.025 > P

†† Percentage of initial value.
VI (P<0.01 for both groups). These measurements were reflected in the calculated values for alveolar/arterial oxygen tension difference. FRC decreased in all groups except Group IV. Changes in Groups I, V and VI were statistically significant (fig. 2). Static lung compliance decreased significantly in Groups V and VI and increased significantly in Group III. There was no significant change in any of the deadspace measurements. There was no significant change in cardiac output in any group. There was a significant increase in pulmonary shunt ratio in Groups I and VI of 4.2% and 6.6% respectively. Oxygen consumption and carbon dioxide output did not change significantly in any group.

DISCUSSION

According to Ingelstedt (1956) the inspired air at the entrance to the trachea should be warmed to about 32°C and be 100% saturated with water. On the other hand, experiences with mechanically ventilated patients have shown that excessive humidification can be as harmful as inadequate humidification (Sladen, 1968; Modell, 1967). Thus it is important that humidification during artificial respiration or in a tracheostomized patient (or both) should be controlled within a relatively narrow range. Rashad and associates (1967) have shown that static compliance decreases significantly after 5 hours of artificial ventilation with dry gases but that this does not occur if the fresh gas is 100% humidified at 35°C.

Colgan, Whang and Gillies (1968) have suggested that a change in FRC or lung compliance may be a better reflection of the extent of alveolar collapse than changes in alveolar arterial oxygen tension difference or in pulmonary shunt ratio. Similar conclusions have been reached by Butler and Smith (1956) and Bernstein (1957). Thus the fall in compliance observed by Rashad and associates (1967) may be the result of partial lung collapse.

In the present study, the most significant changes in lung function occurred when the inspired air was dried to lower than 40% saturation at 15°C or when the temperature was 40°C in spite of 100% humidification. In both these circumstances, a significant fall in arterial oxygen tension and functional residual capacity and an increase in alveolar/arterial oxygen tension difference and pulmonary shunt ratio occurred. These two groups also showed the largest fall in static lung compliance. Although significant falls in FRC and lung compliance occurred in Group V, these were not associated with any significant alteration in gas transfer in the lung. But, because lung collapse of a small extent can be compensated by the changed distribution in pulmonary perfusion, the absence of significant alteration in intrapulmonary gas transfer in group V cannot be regarded as excluding the possibility of some degree of lung collapse, which is suggested by the significant falls in functional residual capacity and lung compliance.

The results in this study would suggest that when the inspired gas is fully saturated, the temperature at which it is administered is not critical between 20°C and 30°C.

REFERENCES


UNE ETUDE DE L'HUMIDIFICATION CHEZ LE CHIEN TRACHEOSTOMISE

SOMMAIRE

Dans le but de déterminer quelles sont les conditions optimales pour l'humidification de l'air inspiré à travers une trachéostomie, on a fait respirer de l'air humidifié, dont on faisait délibérément varier la température entre 15° et 40°C à des chiens trachéostomisés. La saturation de l'air était inférieure à 40% à 15°C, mais complète aux autres températures. Les mesures de la ventilation alvéolaire, de la capacité fonctionnelle résiduelle, de la compliance pulmonaire, de la différence en Po2 alvéolaire/artérielle, du rapport shunt pulmonaire, du débit cardiaque et de la consommation d'oxygène suggèrent que les conditions de fonction pulmonaire, obtenus lorsque les animaux respiraient de l'air complètement saturé à une température entre 20°C et 30°C, étaient satisfaisantes.

EINE UNTERSUCHUNG ÜBER DIE LUFTBEFEUCHTUNG AN TRACHEOTOMIERTEN HUNDEN

ZUSAMMENFASSUNG

Um die optimalen Bedingungen für die Anfeuchtung der durch ein Tracheostoma eingetretene Luft bestimmen zu können, ließ man tracheotomisierte Hunde angefeuchtete Luft einatmen. Die Temperaturen der Luft wurden zwischen 15 Grad und 40 Grad planmäßig variiert. Bei 15 Grad betrug die Luftfeuchtigkeit weniger als 40%, bei den anderen Temperaturen war die Luft jedoch voll mit Feuchtigkeit gesättigt. Es wurden Messungen der alveolaren Ventilation, der funktionellen Residualkapazität der Lungendehnungsfähigkeit, des Unterschiedes in der Sauerstoffspannung zwischen Alveolen und Arterien, Verhältnis des pulmonalen Shunts, der cardialen Austrittsmenge und des Sauerstoffverbrauchs vorgenommen. Daraus ergab sich, daß befriedigende Bedingungen der Lungenfunktion dann zu erzielen waren, wenn die Tiere eine voll mit Feuchtigkeit gesättigte Luft einatmeten deren Temperatur zwischen 20 und 30 Grad lag.

UN ESTUDIO DE HUMECTACION EN PERROS TRAQUEOTOMIZADOS

RESUMEN

Con el fin de determinar las condiciones óptimas para la humectación del aire inspirado a través de la traqueotomía, perros traqueotomizados fueron sometidos a respirar aire húmedo, cuya temperatura fue variada deliberadamente entre 15°C y 40°C. A 15°C, el aire contenía una saturación inferior a 40%, pero estaba completamente saturado a las otras temperaturas. Las mediciones de la ventilación alveolar, capacidad funcional residual, compliance pulmonar, diferencia de Po2 alveolararterial, tasa de shunt pulmonar, gasto cardíaco y consumo de oxígeno, indican que se obtienen condiciones satisfactorias de la función pulmonar cuando los animales respiran aire completamente saturado, administrado a una temperatura comprendida entre 20°C y 30°C.

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