Respiratory effects of warm and dry air at increased ambient pressure

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Thorsen E, Rønnestad I, Segadal K, Hope A. Respiratory effects of warm and dry air at increased ambient pressure. Undersea Biomed Res 1992; 19(2):73–83.—We have measured in 7 divers forced vital capacity (FVC), forced expired volume in 1 s (FEV₁), and forced midexpiratory flow rate (FEF₂₅-₇₅) before and after exposure to dry or humid breathing gas of 35.3°–36.8°C (air) when diving to pressures of 117–600 kPa. The response was compared with the subjects’ reactivity to pharmacologic bronchoprovocation with methacholine. Baseline FEV₁ and FEF₂₅-₇₅ decreased in accordance with increasing gas density. Relative to baseline, there was a significant reduction after the dives in FEV₁ of 4.0 ± 6.1% (P < 0.05) and in FEF₂₅-₇₅ of 8.6 ± 9.7% (P < 0.01) with exposure to dry breathing gas. By analysis of variance the reduction in the lung function variables below baseline were related to the breathing gas characteristic (dry/humid) (P < 0.01), bronchial hyperreactivity (P < 0.02), and ambient pressure (P < 0.02) independently of each other. There was no significant change in FVC after the exposures. Humid breathing gas was considered more comfortable than dry breathing gas, and the upper comfort limit for breathing gas temperature was higher with humid breathing gas. Convective respiratory heat loss was negligible in these experiments, indicating that dry gas itself had a significant bronchoconstrictive effect. Bronchial hyperreactivity may cause increased risk of development of bronchial obstruction and air trapping during diving.

The inhalation of cold and dry gas results in increased airways resistance in normal subjects (1) and asthmatics (2). The response correlates with the response to pharmacologic bronchoprovocation with histamine or methacholine (3, 4). Jammes et al. (5) have shown that the inhalation of cold gas (helium and oxygen mixture) at 25 atm abs resulted in increased airways resistance in divers who had a normal bronchial reactivity to carbachol, and Burnet et al. (6) showed that this effect was related to convective respiratory heat loss.

The inhalation of dry gas results in water loss and changes in the osmolarity of the bronchial mucosa. It has been shown that a change in osmolarity may be as important as heat loss in inducing bronchoconstriction (7, 8), and exercise with warm dry air is
as potent a stimulus to bronchoconstriction as is exercise with cold dry air (9), despite
the greater heat loss from cold dry air. The inhalation of dry air may also result in
airway epithelial damage and inflammation (10).

At increased ambient pressure, pulmonary mechanical function is limited by the
increased density of the breathing gas. Airways resistance increases in proportion to
gas density when flow is turbulent (11). Effects of respiratory heat and water loss will
then add to the pulmonary limitations already imposed by increased gas density,
immersion (fluid shifts and hydrostatic imbalance), and breathing equipment (external
resistance and dead space).

The breathing gas supplied to divers is dry to prevent corrosion and icing in the
gas storage and supply system, but humidifiers can be introduced on the low-pressure
side of the gas supply system. In this study, the bronchial response to exposure to
warm and dry air was compared with the response to warm and humid air in otherwise
identical experimental conditions when diving to pressures of 117–600 kPa.

SUBJECTS AND METHODS

Seven divers (6 male and 1 female), aged 20–25 yr served as subjects. Their
characteristics and baseline pulmonary function given as percentage of the predicted
(12) are shown in Table 1. None of the subjects had ever smoked; all were free of
pulmonary symptoms and had a normal physical examination of their heart and lungs.
Before the experiments, they had all passed the annual medical examination required
for professional diving by the Norwegian Directorate for Public Health. Five subjects
were recruited from the Subaqua Club at the University of Bergen, all of whom were
experienced sport divers and scientific divers for the university. Two subjects were
recruited from the Royal Norwegian Navy where they served as divers. The protocol
for the study was approved by the Ethical Committee of the Norwegian Research
Council for Science and the Humanities. Informed consent was obtained from each
subject.

In two different diving series, described below, the effects of warm and dry breathing
gas were compared with the effects of warm and humid breathing gas, under
otherwise identical experimental conditions. Exposure to dry or humid breathing gas

**TABLE 1**

<table>
<thead>
<tr>
<th>Subject/sex</th>
<th>Age, yr</th>
<th>Height, cm</th>
<th>FVC, %</th>
<th>FEV₁, %</th>
<th>FEF₂₅₋₇₅%, %</th>
<th>PC₂₀, mg·ml⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 M</td>
<td>25</td>
<td>175</td>
<td>93</td>
<td>85</td>
<td>75</td>
<td>2</td>
</tr>
<tr>
<td>2 M</td>
<td>24</td>
<td>180</td>
<td>104</td>
<td>97</td>
<td>80</td>
<td>12</td>
</tr>
<tr>
<td>3 M</td>
<td>24</td>
<td>186</td>
<td>98</td>
<td>103</td>
<td>107</td>
<td>&gt;64</td>
</tr>
<tr>
<td>4 M</td>
<td>22</td>
<td>196</td>
<td>102</td>
<td>104</td>
<td>99</td>
<td>&gt;64</td>
</tr>
<tr>
<td>5 F</td>
<td>22</td>
<td>172</td>
<td>106</td>
<td>104</td>
<td>107</td>
<td>&gt;64</td>
</tr>
<tr>
<td>6 M</td>
<td>21</td>
<td>184</td>
<td>109</td>
<td>98</td>
<td>85</td>
<td>42</td>
</tr>
<tr>
<td>7 M</td>
<td>20</td>
<td>182</td>
<td>100</td>
<td>97</td>
<td>102</td>
<td>&gt;64</td>
</tr>
</tbody>
</table>
was given in random order on different days. For practical reasons, the subjects could not be blinded with respect to the breathing gas characteristic.

Diving series 1

Five subjects performed 2 dives each to pressures of 117, 375, and 600 kPa. The two dives to each pressure were done on different days within 1 wk. The dives to the pressure of 117 kPa were done in a swimming pool, and the dives to the pressures of 375 and 600 kPa were done in the wet pot of the hyperbaric chamber complex at the Royal Naval Base at Haakonsvern, Norway. The bottom time for each dive was 30 min, and the decompression procedures followed were those of the U.S. Navy diving tables. The divers wore 6.4-mm neoprene wet suits (F. Chr. Olsen & Son, Bergen, Norway), and the underwater breathing system was a prototype (designed by Ottestad Breathing Systems A/S Tønsberg, Norway) consisting of a heater and humidifier, and a low-resistance breathing valve integrated in a Comex Pro (Marseille, France) full face mask with an inner (oronasal) mask. The temperature of the breathing gas was continuously monitored with a Fenwal GB 425 MM1 fast response thermistor (response time 0–90% in 300 ms) placed in the oronasal mask (Fenwal Electronics, Framingham, MA). The temperature of the inspired gas was maintained between 35.3° and 36.8°C throughout the exposures, with no systematic differences between the dry gas and humid gas exposures. Relative humidity was measured with a Vaisala HMP 42 U humidity probe (Vaisala OY, Helsinki, Finland) at the output of the humidifier at a temperature of 37°C at 100 kPa ambient pressure before the dives. The relative humidity was 50–100% depending on gas flow, but humidity was not continuously monitored during the dives due to technical difficulties. Ambient water temperature was 10°–12°C. At the bottom depth, the divers performed physical activity in the form of swimming against a resistance (trapeze) that could be regulated. The work load was standardized for each depth, but the work load was not measured. Based on previous experience it was classified as moderate at 375 and 600 kPa and hard at 117 kPa. One subject did not take part in the exposures at 375 kPa and 1 subject did not take part in the exposures at 600 kPa. As a control exposure, they breathed warm and dry, and warm and humid air for 1 h resting in room air of 22°C at 100 kPa ambient pressure.

Diving series 2

Four divers, 2 of whom also participated in diving series 1, dived to a pressure of 135 kPa for 4 h in the pool at the Norwegian Underwater Technology Centre, once with warm and dry breathing gas and once with warm and humid breathing gas. The same diving equipment as in series 1 was used. Inspired temperature of the breathing gas was 35.5°–36.8°C. During the dives they did three exercise bouts of 15-min duration at moderate intensity swimming against the resistance, commencing at 5, 120, and 210 min into the dive. In between they did light work consisting of assembling a puzzle of valves and pipes on a rig; this simulates the activity and duration of an operational dive or “lock-out.”
Pulmonary function

Forced vital capacity (FVC), forced expired volume in 1 s (FEV₁), and forced midexpiratory flow rate (FEF₂₅₋₇₅) were measured on a 570 Wedge Spirometer (MedScience, St. Louis, MO). The highest values from three maneuvers, not differing by more than 5% from the highest FVC, were used for analysis. In series 1, measurements were taken before entering the wet pot of the chamber or the pool and as soon as possible after surfacing before the start of decompression. In series 2, the divers went to the surface and measurements were taken before and after each bout of exercise. Measurements before and after the 4-h diving period served as the controls. The divers were dressed in the diving suits when the measurements were taken. The spirometer was placed in the immediate vicinity of the pool or wet pot of the hyperbaric chamber, and the measurements could then be taken 1–2 min after surfacing, or 3–5 min after the end of the exercise challenges. All values were corrected to the BTPS condition.

In series 2, measurements of static and dynamic lung volumes and flows, transfer factor for carbon monoxide (TlCO), and the single-breath oxygen test with determination of the slope of phase III of the nitrogen washout (ΔN₂) and closing volume (CV) were done 1 h before the dives and as soon as practically possible after the dives (30–45 min). Dynamic lung volumes and flows and TlCO were measured according to the standardized procedures of the European Community for Coal and Steel (13), and the single-breath oxygen test according to the standardized procedures of the National Heart and Lung Institute (14). Static lung volumes were measured by the multibreath nitrogen-washout test. All measurements were taken on a Gould model 1000IV Computerized Pulmonary Function Laboratory (Gould Inc., Dayton, OH). All values were corrected to the BTPS condition.

A questionnaire for subjective evaluation of pulmonary symptoms and comfort of the breathing gas temperature and humidity was administered after the dives in both diving series. The divers were asked to score comfort on multistep scales from intolerably warm to intolerably cold and from very humid to very dry. In addition, a direct comparison of comfortable temperature of dry and humid gas was determined in a separate test at 117 kPa in series 1. After having done the second lung function test, the divers reentered the pool and the breathing gas temperature was gradually increased or decreased from 37°C at a rate of 1°C · min⁻¹. A signal was given by the diver when an optimal and comfortable temperature was obtained.

Bronchial reactivity

Bronchial reactivity to methacholine was measured according to the method of Cockcroft et al. (15). Doubling concentrations of methacholine, starting with 0.25 mg · ml⁻¹, were inhaled from a Parin nebulizer for 2 min of tidal breathing. Forced expiratory volumes were measured 1 and 3 min after each dose. The time between each administered dose was 5 min. The control was isotonic saline. Bronchial reactivity was expressed as the provocative concentration causing a 20% reduction in FEV₁ (PC₂₀). The maximal concentration of methacholine administered was 64 mg · ml⁻¹. The methacholine challenges were done 2–4 wk after the diving experiments.
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Data processing and statistics

Changes in the lung function variables at each pressure were expressed as percent change from the corresponding baseline. The effects of dry and humid breathing gases were compared by unpaired Student’s t test. Two-way analysis of variance (ANOVA) was used to find correlations between the change in the lung function variables and the breathing gas characteristic (dry vs. humid breathing gas), subjects’ characteristics (bronchial hyperreactivity vs. normal bronchial reactivity), ambient pressure, and sex. The scores regarding comfort of the breathing gas were compared with the Pearson chi-squared test. A P value < 0.05 was considered significant.

RESULTS

The subjects’ FVC and FEV₁ were within the normal predicted range, but FEF₂₅₋₇₅% was lower than predicted (<80%) in subject 1, who had a history of childhood asthma and who was hyperreactive to methacholine, defined as a PC₂₀ = 8 mg·ml⁻¹.

Baseline FEV₁ and FEF₂₅₋₇₅% were reduced at 375 and 600 kPa in accordance with the increased density of the breathing gas (Fig. 1). The density dependence of FEV₁ and FEF₂₅₋₇₅% was not different in the subject with methacholine hyperreactivity compared with the nonreactive subjects (Fig. 1). His reduction in FEV₁ at 375 and 600 kPa was 25.5 and 45.2%, and in FEF₂₅₋₇₅% 37.6 and 50.6%. The nonreactive subjects had a reduction in FEV₁ at 375 and 600 kPa of 20.3–23.6% and 42.0–45.3%, and in FEF₂₅₋₇₅% of 25.8–42.6% and 39.2–54.8%. FVC did not show any significant depth-dependent changes. In series 2 there were no significant differences in the baselines taken as the measurements before each exercise bout. The changes in FEV₁ and FEF₂₅₋₇₅%, relative to baseline, after the dives with dry and humid breathing gas are shown in Figs. 2 and 3.

When all exposures to dry and humid breathing gas were pooled there was a reduction in FEV₁ of 4.0 ± 6.1% after exposure to dry breathing gas and a reduction of 1.1 ± 3.2% after exposure to humid breathing gas (P < 0.05). The reduction in FEF₂₅₋₇₅% was 8.6 ± 9.7% and 0.9 ± 6.3% (P < 0.01), respectively. When comparing corresponding exposures at equivalent pressures (n = 5 at 100 and 117 kPa, n = 4 at 135, 375, and 600 kPa), only the change in FEF₂₅₋₇₅% after exposure to dry breathing gas at 600 kPa proved to be significant (P < 0.05), Fig. 2.

In the two-way ANOVA, the changes in FEV₁ and FEF₂₅₋₇₅% were shown to be dependent on the breathing gas characteristics (P < 0.01), bronchial hyperreactivity (P < 0.02), and ambient pressure (P < 0.02), independently of each other (Table 2). The response shown by the female subject was no different from the response shown by male subjects. There was no significant change in FVC after the dives.

Both humid and dry breathing gas of 35.3°–36.8°C were subjectively within tolerable limits, with no significant difference in the rating of the comfort of breathing gas temperature, but humid breathing gas was reported to be more comfortable than dry breathing gas at all pressures (P < 0.01) (Table 3). Dryness of lips and mouth was reported with exposure to dry breathing gas, but airway symptoms like coughing and mucus production were not reported. At 117 kPa the optimal temperature of the breathing gas chosen by the divers was 4.8° ± 1.2°C (P < 0.01) higher with humid breathing gas compared with dry breathing gas, 35.8° vs. 31.0°C. The lower comfortable limit of breathing gas temperature was not estimated.
In series 2 there were no significant changes in static and dynamic lung volumes and flows, diffusion capacity, or distribution of ventilation 1 h after the dives, neither with exposure to dry breathing gas nor with exposure to humid breathing gas (data not shown).

DISCUSSION

The results show a reduction in maximal expiratory flows after breathing warm and dry gas in subjects simulating common professional diving activity. All subjects were medically qualified for professional diving. The subject who was hyperreactive to bronchoprovocation with methacholine had a larger reduction in the lung function variables than the nonreactive subjects. The results are in agreement with the studies of Schoeffel et al. (7) and Antoniou et al. (17) at normal atmospheric pressure in
which dry air challenge or osmotic challenge induces a bronchoconstrictive response in subjects with bronchial hyperreactivity as well as in normal subjects. No residual effect of dry gas exposure for 4 h was detected.

The effect was related to ambient pressure, but that does not mean that the response is dependent on pressure, because baseline values for FEV₁ and FEF₂₅₋₇₅% are reduced with increasing pressure. At 375 and 600 kPa, FEV₁ and FEF₂₅₋₇₅% are reduced because of the increased airways resistance imposed by the increased gas density (11). An additional bronchoconstrictive response will cause a relatively larger reduction in flow under these circumstances than at normal pressure and gas density. The reduction in FEF₂₅₋₇₅% was larger than the reduction in FEV₁, 8.6 and 4.0%, respectively. FEF₂₅₋₇₅% is derived from the effort-independent part of the flow-volume loop, whereas FEV₁ contains both the effort-dependent part and effort-independent part of the flow-volume loop. The density-dependent reduction in FEF₂₅₋₇₅% was larger than the density-dependent reduction in FEV₁. This may explain the larger reduction in FEF₂₅₋₇₅%. FEF₂₅₋₇₅% is more sensitive to small airways changes than FEV₁. Conditioning of inspired air may not be complete in the upper airways, as shown in the study by Chandler et al. (18) in which a drop in esophageal temperature was demonstrated with exercise with cold air, and in the study of Gilbert et al. (19) in which the temperature of inspired gas had not reached body temperature at the fourth branching of the bronchial tree. High gas density may also affect the kinetics of humidification and warming of inspired gas, and its effect on small airways cannot be excluded.
Fig. 3. Changes in FEV₁ and FEF₂₅₋₇₅% relative to baseline after the exposures to dry (solid bars) and humid breathing gas (open bars) in series 2. Means ± 1 SD (n = 4) are given. CL = control. WL 1–3 = work loads 1–3.

### TABLE 2

**ANOVA Table Showing the Relationships Between the Changes in the Lung Function Variables and Breathing Gas Characteristic, Bronchial Reactivity, and Pressure**

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FEV₁</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry gas</td>
<td>196</td>
<td>1</td>
<td>12.75</td>
<td>0.001</td>
</tr>
<tr>
<td>Bronchial hyperreactivity</td>
<td>153</td>
<td>1</td>
<td>9.94</td>
<td>0.003</td>
</tr>
<tr>
<td>Pressure</td>
<td>139</td>
<td>2</td>
<td>4.52</td>
<td>0.016</td>
</tr>
<tr>
<td>Within variance</td>
<td>706</td>
<td>46</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FEF₂₅₋₇₅%</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry gas</td>
<td>1072</td>
<td>1</td>
<td>24.59</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Bronchial hyperreactivity</td>
<td>261</td>
<td>1</td>
<td>6.00</td>
<td>0.017</td>
</tr>
<tr>
<td>Pressure</td>
<td>908</td>
<td>2</td>
<td>10.41</td>
<td>0.003</td>
</tr>
<tr>
<td>Within variance</td>
<td>2006</td>
<td>46</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 3

<table>
<thead>
<tr>
<th>Humidity</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comfortable</td>
<td>Uncomfortable, too Dry</td>
</tr>
<tr>
<td>Dry gas</td>
<td>4</td>
</tr>
<tr>
<td>Humid gas</td>
<td>14</td>
</tr>
</tbody>
</table>

*aThe numbers indicate exposures that were rated as comfortable or not when breathing dry or humid gas.

Significant difference in scores between dry and humid gas (P < 0.01).

Differences in total evaporative respiratory heat loss and respiratory water loss may have occurred since minute ventilation and humidity were not measured. However, the divers’ in-water activities were standardized and the same under both experimental conditions, and the output of the humidifier was controlled at 100 kPa ambient pressure. When tested at a pressure of 3.7 MPa, the humidifier supplied divers exercising at 200 W with a breathing gas of 40–60% relative humidity (Knudsen et al., NUTEC report 23-86). The respiratory heat loss (RHL) consists of a convective and an evaporative part due to humidification of the breathing gas as shown by the formula

\[ RHL = V_e \cdot \rho \cdot C_p \cdot (T_e - T_i) + V_e \cdot 0.58 \cdot (WC_e - WC_i) \]

where \( V_e \) is minute ventilation, \( \rho \) is gas density, \( C_p \) is specific heat, \( T_e \) and \( T_i \) are expired and inspired gas temperatures, 0.58 is the latent heat of evaporation, and \( WC_e \) and \( WC_i \) are the water contents of expired and inspired gas at the actual \( T_e \) and \( T_i \). In this study the convective part of RHL is very small because \( T_e \) and \( T_i \) are very close and \( T_i \) did not differ between the dry gas and humid gas exposures. Assuming a \( V_e \) of 50 liter \( \cdot \) min\(^{-1}\) during the working periods at pressure, the calculated evaporative RHL with dry gas exposure was 85 and 92 W at 375 and 600 kPa. At atmospheric pressure with a \( V_e \) of 50 liter \( \cdot \) min\(^{-1}\) and \( C \) relative humidity of 50%, a total RHL of 90 W would have been obtained if \( T_i \) was lowered to 9.0°C. A RHL of that order does not induce bronchoconstriction in normal subjects (9).

Results of the lung function measurements may, in addition to the effects of the increased gas density, have been influenced by wearing a diving suit when the measurements were taken, which could restrict the movements of the thorax. Furthermore, immediately after the dives, residual effects of the redistribution of blood volume in the thorax due to immersion may have influenced the results. However, there was no change in FVC after the dives, and the experimental conditions were the same whether the exposure was to dry or humid breathing gas. The inhalation to total lung capacity before a forced expiratory maneuver has a bronchodilatory effect (20). This would have reduced the difference between the results of the exposure to dry and humid breathing gas.

The time course of the changes in FEV\(_1\) during and after bronchoprovocation with isocapnic hyperventilation has been studied by Blackie et al. (21). They found no change in FEV\(_1\) during hyperventilation. Mean times after hyperventilation until maximal bronchoconstriction were 6–12 min. These authors concluded that either
hyperventilation itself inhibits bronchoconstriction or that the mechanisms that induce bronchoconstriction operate after, rather than during, hyperventilation. In our studies, pulmonary function measurements were taken 3–5 min after the challenge, and the bronchoconstrictory response may not have been at its maximum at that time.

A significant interindividual variability in the response was ascribed to bronchial hyperreactivity, which is in agreement with other studies showing a very close relationship between the responses to pharmacologic and physical bronchoprovocation (3, 4). The mechanisms for the bronchial responses to physical bronchoprovocation are not known. Different mechanisms may be involved depending on the stimulus. There may be a neurogenic response due to stimulation of thermal and irritant receptors in the bronchial mucosa, or a response mediated by locally released transmitters. The response can be triggered by respiratory heat loss due to warming and humidification of the breathing gas, and by local changes in osmolarity of the bronchial mucosa due to water loss.

Humid breathing gas was considered more comfortable than dry breathing gas by all subjects at all pressures, and the upper comfortable limit for breathing gas temperature was higher with humid breathing gas. In deep saturation diving with helium and oxygen mixtures, where respiratory heat loss is considerable, a higher comfortable breathing gas temperature could be obtained by humidifying the breathing gas, thereby reducing total heat loss.

Neither professional divers nor sport divers are screened for bronchial reactivity. Subjects with bronchial hyperreactivity may be at increased risk of developing bronchial obstruction during diving with its increased risk of air trapping and gas embolism. In professional diving, warming and humidifying the breathing gas will be of benefit to prevent a bronchoconstrictory stimulus that will add to the limitations of pulmonary function already present.

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