

Characteristics of the respiratory mechanical and muscle function of competitive breath-hold divers

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Abstract Competitive breath-hold divers (BHD) employ glossopharyngeal insufflation (GI) to increase intrapulmonary oxygen stores and prevent the lungs from dangerous compressions at great depths. Glossopharyngeal insufflation is associated with inflation of the lungs beyond total lung capacity (TLC). It is currently unknown whether GI transiently over-distends the lungs or adversely affects lung elastic properties in the long-term. Resting lung function, ventilatory drive, muscle strength, and lung compliance were measured in eight BHD who performed GI since 5.5 (range 2–6) years on average, eight scuba divers, and eight control subjects. In five BHD subsequent measures of static lung compliance (Cstat) were obtained after 1 and 3 min following GI. Breath-hold divers had higher than predicted ventilatory flows and volumes and did not differ from control groups with regard to gas transfer, inspiratory muscle strength, and lung compliance. A blunted response to CO₂ was obtained in BHD as compared to control groups. Upon GI there was an increase in mean vital capacity (VC_{GI}) by

1.75 ± 0.85 (SD) L compared to baseline ($p < 0.001$). In five BHD Cstat raised from 3.7 (range 2.9–6.8) L/kPa at baseline to 8.1 (range 3.4–21.2) L/kPa after maximal GI and thereafter gradually decreased to 5.6 (range 3.3–8.1) L/kPa after 1 min and 4.2 (range 2.7–6.6) L/kPa after 3 min ($p < 0.01$). We conclude that in experienced BHD there is a transient alteration in lung elastic recoil. Resting lung function did not reveal a pattern indicative of altered lung ventilatory or muscle function.

Keywords Static lung compliance · Ventilatory drive · Apnea · Glossopharyngeal insufflation · Diving

Introduction

The ability to tolerate prolonged apnea is a prerequisite to set time or depth records in competitive breath-hold diving (Muth et al. 2005). Unlike some diving birds or mammals, humans are not adapted to an aquatic existence and their mean breath-hold duration usually does not exceed a few minutes (Parkes 2006). In order to increase pulmonary oxygen stores and thereby breath-hold duration, to dispose of greater air volume to equalize cranial air cavities (ears, sinuses) at depth, and to reduce dangerous chest compression at great depths, a particular breathing technique named glossopharyngeal breathing is employed by elite human breath-hold divers (BHD) (Muth et al. 2005; Lindholm and Nyren 2005). After filling the lungs to total lung capacity (TLC), a mouthful of air with the glottis closed is compressed by the oropharyngeal muscles and then forced into the lungs, opening the glottis just for the gulping maneuver. This glossopharyngeal pumping is repeated several times until a sensation of fullness occurs. Loring et al. (2007) recently reported that in elite breath-hold divers TLC may

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increase with glossopharyngeal pumping by up to 47%. The authors also showed that the increase in intrathoracic gas volume was accompanied by an increase in transpulmonary pressure of up to 80 cmH₂O and a maximum in intrapulmonary pressure of 109 cmH₂O. These data indicate that some individuals can withstand transpulmonary pressures and volumes far greater than those to which lungs would normally be exposed to. Though it has recently been speculated that the time course for lung recoil pressure recovery may be prolonged after GI (Seccombe et al. 2006), it has not yet been shown whether or not GI transiently over distends the lungs or adversely affects lung elastic properties in the long-term.

We explored pulmonary mechanical function of eight experienced male elite BHD by measurement of lung volumes and lung compliance at rest and during GI. The divers were considered “elite” when they were performing at least three competitions per year and won competitions in their best diving discipline. To characterize whole lung function of these BHD we compared their respiratory mechanical and respiratory muscle function to matched control groups of eight male scuba (self-contained underwater breathing apparatus) divers and eight healthy non-diving individuals each. We hypothesized that lung function testing of experienced BHD might reveal a pattern of ventilatory and/or mechanical airway changes due to repeated exposure to GI. Further, we measured static lung compliance at different timepoints after GI in five BHD in order to evaluate the time course of changes in mechanical properties of the lung caused by GI.

Methods

Subjects

Eight BHD able to perform GI, eight recreational scuba divers with a diving history of more than 100 dives, and eight non-diving subjects matched for age and body mass index (BMI) were invited to participate (Table 1). All subjects were healthy males with no history of cardiorespiratory diseases. The study protocol has been approved by the Ethics Committee of the Albert-Ludwigs-University at Freiburg, Germany, and was performed in accordance with the ethical standards set by the Declaration of Helsinki in the year 2000. All subjects signed their informed consent prior to the participation in the study.

Lung flows and volumes

Body plethysmography was performed using a constant volume body plethysmograph (MasterLab[®], Viasys, Höchberg, Germany) according to current ATS/ERS guidelines

Table 1 Characteristics of subjects

| | BHD <i>N</i> = 8 | Divers <i>N</i> = 8 | Controls <i>N</i> = 8 |
|--------------------------|------------------|---------------------|-----------------------|
| Age (year) | 30 ± 8 | 31 ± 8 | 29 ± 8 |
| Height (cm) | 183 ± 7 | 178 ± 7 | 179 ± 8 |
| Weight (kg) | 77 ± 10 | 85 ± 17 | 74 ± 9 |
| BMI (kg/m ²) | 23 ± 3 | 27 ± 4 | 23 ± 3 |
| Smoking never | 6 | 8 | 7 |
| Former smoking | 1 | 0 | 1 |
| Current | 1 | 0 | 0 |

Values displayed as mean ± SD or totals

BHD breath-hold divers, BMI body mass index

(Miller et al. 2005; Wanger et al. 2005). Maximal inspiratory vital capacity (VC) served as baseline measure for the comparison of lung volumes before and during GI (VC_{GI}).

Gas exchange and control of breathing

The single breath method was applied for determination of the carbon monoxide transfer factor and coefficient ($T_{L,CO}$) (MacIntyre et al. 2005). Values were corrected for the hemoglobin concentration and to BTPS. Breathing frequency (f_b), tidal breathing ventilation per minute ($V'T$), and mouth occlusion pressure at 0.1 s ($P_{0.1}$) were measured as a determinant of respiratory drive. For $P_{0.1}$ ($P_{0.1}$ rest) measurements the subjects were required to perform tidal breathing through a mouthpiece. Ten occlusions of the airway in random order at 0.1 s after the initiation of inspiration were measured for determination of $P_{0.1}$ by the laboratory system (MasterLab[®], Viasys, Höchberg, Germany). The effect of increased CO₂ in respiratory drive ($P_{0.1}$ CO₂) was measured using a mixture of 6% CO₂ in O₂, which was added to the breathing circuit. Drive measurements under CO₂ rebreathing were started after reaching a steady state in $V'T$ and f_b . Closure of the valve occurred according to the previous mentioned method of $P_{0.1}$ measurement unexpectedly for the subject during tidal breathing according to recent guidelines (ATS/ERS 2002). The measurements of $P_{0.1}$ rest and $P_{0.1}$ CO₂ were averaged in order to determine the effects on respiratory drive.

Respiratory muscle strength

Maximal voluntary inspiratory pressure sustained for one second (P_Imax) at residual volume (RV) was measured using a ZAN100 pneumotachograph as a determinant of volitional overall respiratory muscle strength (ZAN[®] GmbH, Oberthulba, Germany). Subjects were asked to exhale to RV, followed by a maximal inspiratory maneuver against occluded airways (occlusion time 2 s). At least five acceptable measurements had to be performed and the overall best value was determined as P_Imax. Tests were

performed and normal values calculated according to previous recommendations (Windisch et al. 2004; ATS/ERS 2002).

Bilateral anterior magnetic phrenic nerve stimulation

Bilateral anterior magnetic phrenic nerve stimulation for non-volitional determination of respiratory muscle strength was performed using two magnetic stimulators (Magstim[®] 200, Magstim[®] Inc., Wales, UK) at maximal output (100%) with two 45 mm figure-eight coils (Magstim[®] Inc., Wales, UK) in order to ensure supramaximal stimulation of the phrenic nerve, as has been demonstrated previously (Mador et al. 2002). Therefore, supramaximality has not been retested in the current study. Both magnetic stimulators were triggered simultaneously with an automated impulse-release derived from the computer system (ZAN[®] GmbH, Oberthulba, Germany). An inspiratory pressure trigger, i.e. twitch mouth pressure (TwPmo) during inspiratory pressure triggering was used at -0.5 kPa, as has been described previously (Windisch et al. 2005). Subjects were asked to perform tidal breathing. At functional residual capacity level (FRC) the subjects were asked to inhale gently against the occluded valve. The magnetic stimulation occurred automatically after reaching the triggering threshold at -0.5 kPa. Each measurement was followed by a 30 s break in order to evade twitch potentiation. FRC, f_b and the time between triggerimpulse and pressure maximum of TwPmo were automatically calculated by the computer system. The pressure and the inspiratory flow during triggerimpulse were measured to control adherence to trigger criteria and to ensure that no critical intrapulmonary volume change occurred during the maneuver. TwPmo was measured until five acceptable pressure tracings were achieved, according to predefined and previously published criteria (Windisch et al. 2005).

Static and dynamic pulmonary compliance

The esophageal pressure method was used for the measurement of lung compliance. Esophageal pressure was used as a determinant of transpulmonary pressure. All measurements were performed with the subjects sitting in an upright comfortable position in a body plethysmograph. The subjects were breathing through the spirometer in order to register the volume change. Pressure curves were recorded using a conventional balloon catheter (ZAN[®] GmbH, Oberthulba, Germany). Firstly, the catheter was placed through an anesthetized nostril into the stomach. While pulling the catheter backwards the flip in the pressure signal from positive to negative recordings marked the entrance into the esophagus. The correct positioning of the catheter in the mid-third part of the esophagus was

monitored online in order to minimize disturbance of the signal through the heart beat. The esophageal balloon was filled with 1.5 mL air over a three-way tap and a syringe, to ensure correct pressure transduction. No recordings were done during esophageal contractions. The standardization of volume history occurred by preceding measurements of lung volumes. Dynamic compliance (C_{dyn}) was registered during quiet breathing and a respiratory rate between 10/min and 20/min. Only closed curves with clearly determined points of reversal at the end of inspiration and expiration were accepted. At least ten pressure–volume curves were registered and the mean value calculated. The determination of the static compliance (C_{stat}) was carried out during gentle passive non-interrupted expiration from TLC ($C_{stat_{rest}}$) or TLC after GI ($C_{stat_{GI}}$). At least three technically acceptable curves had to be achieved for determination of $C_{stat_{rest}}$. For determination of C_{stat} the slope of the curve was used as given out by the body plethysmographic software (MasterLab[®], Viasys, Höchberg, Germany).

Glossopharyngeal insufflation

All BHD performed maximal GI at least three times. The number of gulps needed until reaching maximal GI level (GI_{max}) was counted. VC_{GI} was measured as the slow expired VC for determination of surplus pumped air. For $C_{stat_{GI}}$ the subject breathed in at the spirometer up to TLC and performed the glossopharyngeal pumping freely. Then, without airleak, a slow and gentle passive non-interrupted exhalation was performed while connected to the spirometer. The volume range over which $C_{stat_{GI}}$ was determined as the slope of the curve was between 80 and 50% of estimated TLC using the body plethysmographic software. The narrow range between 80 and 50% proved to be the most stable part of the curve, since the opening of the glottis at the beginning of exhalation caused signal disturbances and lower parts of the curve are expected to represent normal lung volumes. For $C_{stat_{GI}}$ measurements the balloon was filled with 0.5 mL of air in order to avoid signal disturbance through the elastic properties of the balloon while measuring at lung volumes above TLC.

In five BHD subsequent measurements of C_{stat} following a GI_{max} maneuver were performed on a different occasion in order to avoid tiredness and exhaustion by multiple GI maneuvers. C_{stat} was measured before ($C_{stat_{rest}}$) and at GI_{max} ($C_{stat_{GI}}$). In addition, C_{stat} was investigated one minute ($C_{stat_{1\ min}}$) and three minutes ($C_{stat_{3\ min}}$) after glossopharyngeal insufflation. These measurements were performed according to the measurement of $C_{stat_{rest}}$. The exhaled volumes from TLC to FRC were registered in order to prove comparability between these maneuvers at different points in time after GI.

Statistical analysis

The data were analyzed using SigmaStat® 2.0 for Windows® (SSI, San Jose, CA, USA). Results are expressed as means (SD) or as median (range). All variables were tested for normal distribution and equal variance. Paired *t* tests and one-way ANOVA for repeated measurements with pair wise multiple comparison procedures (Student-Newman-Keuls Method) were used to test statistical differences between groups (BHD vs. scuba divers vs. non-diving controls). A *p* value of <0.05 was considered statistically significant.

Results

BHD had performed apnea training for 5.5 (range 2–6) years. Their personal best values for static apnea, i.e. holding breath for as long as possible with the body either in the water or at the surface were 326 (range 270–538) s. The eight scuba divers had a diving history of 240 (range 150–1,000) scuba dives. BHD, scuba divers, and controls did not differ significantly with respect to age or anthropometric data (Table 1).

Forced expiratory flows and volumes of all groups were within the normal range (Table 2). The groups did not differ significantly with regard to flows and volumes. Divers and controls had higher forced expiratory volume than predicted. BHD tended to have the highest peak expiratory flows ($p < 0.1$) of all groups. The forced expiratory volume in 1 s/forced vital capacity (FEV_1/FVC) ratio was significantly reduced in BHD compared with non-diving controls ($p < 0.05$) and tended to be reduced compared with the scuba divers ($p < 0.1$). Body plethysmographic measurements of static lung volumes and airway resistance yielded normal values without significant differences between groups (Table 3). Normal gas transfer values were measured in all subjects.

In the BHD there was a significantly diminished response of $P_{0.1} CO_2$, $V'T$, and f_b compared to both scuba divers and control subjects ($p < 0.05$) (Table 4).

The P_{Imax} of BHD (14.2 ± 1.4 kPa), scuba divers (14.3 ± 2.1 kPa), and controls (13 ± 1.6 kPa) were normal and did not differ significantly between groups. The T_{wPmo} of BHD (1.6 ± 0.4 kPa), scuba divers (1.9 ± 0.4 kPa), and controls (1.6 ± 0.3 kPa) also revealed no significant differences between groups.

$C_{stat_{rest}}$ did not differ significantly between groups (Table 5); the BHD though tended to have highest $C_{stat_{rest}}$ values ($p < 0.1$). There was no difference between groups with regard to dynamic lung compliance.

All BHD were able to perform a maximal GI maneuver. They needed 19 (range 13–75) single glossopharyngeal

Table 2 Expiratory flows and volumes (absolute and predicted values)

| | BHD <i>N</i> = 8 | Divers <i>N</i> = 8 | Controls <i>N</i> = 8 |
|------------------|-------------------|---------------------|-----------------------|
| FEV_1 (L) | 4.98 ± 0.73 | 4.89 ± 0.49 | 4.88 ± 0.49 |
| (%pred) | 113 ± 13 | 117 ± 10 | 115 ± 11 |
| FVC (L) | 6.81 ± 1.61 | 6.03 ± 0.52 | 5.71 ± 0.69 |
| (%pred) | 124 ± 28 | 118 ± 11 | 110 ± 16 |
| VC (L) | 6.85 ± 1.61 | 6.07 ± 0.51 | 5.73 ± 0.67 |
| (%pred) | 110 ± 24 | 104 ± 8 | 98 ± 14 |
| FEV_1/FVC | $0.75 \pm 0.09^*$ | 0.81 ± 0.06 | 0.86 ± 0.05 |
| PEF (L/s) | 12.6 ± 4 | 9.5 ± 1.7 | 10.2 ± 1.9 |
| (%pred) | 129 ± 38 | 102 ± 19 | 107 ± 20 |
| MEF_{75} (L/s) | 9.9 ± 3.6 | 9 ± 1.4 | 9.2 ± 1.5 |
| (%pred) | 106 ± 37 | 101 ± 15 | 103 ± 20 |
| MEF_{50} (L/s) | 5.7 ± 2.5 | 5.6 ± 1.2 | 6.5 ± 1.2 |
| (%pred) | 87 ± 36 | 90 ± 20 | 104 ± 20 |
| MEF_{25} (L/s) | 2.3 ± 0.9 | 2.3 ± 0.6 | 2.7 ± 0.9 |
| (%pred) | 63 ± 22 | 70 ± 21 | 80 ± 20 |

Values displayed as mean \pm SD

BHD breath-hold diver, MEF_{25-75} forced mid-expiratory flow, FEV_1 forced expiratory volume in one second, FVC forced vital capacity, PEF peak expiratory flow, VC vital capacity during slow exhalation

* $p = 0.01$ versus controls

Table 3 Body plethysmographic lung function data and gas transfer

| | BHD <i>N</i> = 8 | Divers <i>N</i> = 8 | Controls <i>N</i> = 8 |
|------------------------------------|------------------|---------------------|-----------------------|
| R_{eff} (kPa s/L) | 0.16 ± 0.07 | 0.15 ± 0.05 | 0.15 ± 0.06 |
| sG_{aw} (s^{-1} kPa $^{-1}$) | 1.58 ± 0.67 | 2.04 ± 0.79 | 1.92 ± 0.52 |
| RV (L) | 1.78 ± 0.39 | 1.48 ± 0.23 | 1.65 ± 0.52 |
| FRC (L) | 4.17 ± 0.46 | 3.27 ± 0.26 | 3.59 ± 0.7 |
| TLC (L) | 8.64 ± 1.52 | 7.55 ± 0.55 | 7.38 ± 1.52 |
| RV/TLC (%) | 21.26 ± 5.37 | 19.62 ± 2.76 | 21.96 ± 4.03 |
| FRC/TLC | 0.5 ± 0.05 | 0.43 ± 0.03 | 0.49 ± 0.06 |
| V_A (L) | 7.74 ± 0.89 | 7.16 ± 0.23 | 7.19 ± 1.25 |
| $T_{L,CO}$ SB (mmol/min/kPa/L) | 12.1 ± 0.7 | 12.4 ± 1.6 | 12.7 ± 2.1 |
| $T_{L,CO}/V_A$ (mmol/min/kPa/L) | 1.6 ± 0.2 | 1.7 ± 0.2 | 1.8 ± 0.3 |

Values displayed as mean \pm SD

%pred percent of predicted, BHD breath-hold diver, $T_{L,CO}$ SB diffusing capacity for the lungs measured using carbon monoxide in a single breath, $T_{L,CO}/V_A$ diffusing capacity for carbon monoxide per unit of alveolar volume, FRC functional residual capacity, RV residual volume, R_{aw} airway resistance, sG_{aw} specific airway conductance, TLC total lung capacity, V_A alveolar volume

pumpings until achieving their individual maximal lung capacity (GI_{max}). There was no correlation between the number of glossopharyngeal pumping maneuvers needed to achieve GI_{max} and other parameters assessed in this study. Compared to baseline, there was an increase in VC_{GI} by

Table 4 Ventilatory drive

| | BHD <i>N</i> = 8 | Divers <i>N</i> = 8 | Controls <i>N</i> = 8 |
|------------------------------------|------------------|---------------------|-----------------------|
| f_b Rest (breath/min) | 14 ± 4 | 17 ± 4 | 18 ± 3 |
| f_b CO ₂ (breath/min) | 13 ± 5* | 18 ± 4 | 21 ± 4 |
| V^T Rest (L/min) | 17 ± 9 | 17 ± 6 | 14 ± 2 |
| V^T CO ₂ (L/min) | 23 ± 8* | 31 ± 4 | 34 ± 9 |
| $P_{0.1}$ Rest (kPa) | 0.14 ± 0.08 | 0.23 ± 0.09 | 0.22 ± 0.08 |
| $P_{0.1}$ CO ₂ (kPa) | 0.27 ± 0.19* | 0.62 ± 0.24 | 0.68 ± 0.42 |

Values displayed as mean ± SD

BHD breath-hold diver, f_b breathing frequency, V^T tidal breathing ventilation per minute, $P_{0.1}$ mouth occlusion pressure at 0.1 s after the initiation of inspiration

* $p < 0.05$ versus divers/controls

Table 5 Static and dynamic lung compliance

| | BHD <i>N</i> = 8 | Divers <i>N</i> = 8 | Controls <i>N</i> = 8 |
|----------------|------------------|---------------------|-----------------------|
| C stat (kPa) | 4.01 ± 1.52 | 3.37 ± 0.91 | 2.73 ± 0.69 |
| C stat (%pred) | 136 ± 60 | 118 ± 31 | 95 ± 17 |
| C stat/TLC | 0.5 ± 0.2 | 0.4 ± 0.1 | 0.4 ± 0.1 |
| C dyn (kPa) | 3.09 ± 0.62 | 2.78 ± 0.56 | 2.64 ± 0.72 |
| C dyn (%pred) | 102 ± 17 | 97 ± 19 | 91 ± 18 |

Values displayed as mean ± SD

BHD breath-hold diver, C stat static compliance at rest, C dyn dynamic compliance at resting breathing, TLC total lung capacity, %pred percent of predicted

25.3% on average of 1.75 ± 0.85 l ($p < 0.001$). Accordingly, $C_{stat_{GI}}$ significantly increased to 6.8 ± 3.3 L/kPa ($p < 0.01$) measured during slow, passive exhalation from GI_{max} . At GI_{max} half of the subjects reported a feeling of “fullness” whereas the remainder stated that they sensed a high “pressure” feeling.

In five BHD subsequent measurements of Cstat were available. $C_{stat_{rest}}$ rose from 3.7 (range 2.9–6.8) L/kPa to $C_{stat_{GI}}$ 8.1 (range 3.4–21.2) L/kPa at GI_{max} and thereafter gradually decreased to 5.6 (range 3.3–8.1) L/kPa after 1 min ($C_{stat_{1\ min}}$) and to 4.2 (range 2.7–6.6) L/kPa after 3 min ($C_{stat_{3\ min}}$). Figure 1 shows the means (SD) of Cstat measurements across different timepoints. The exhaled lung volumes from TLC to FRC, however, did not differ significantly between the different measurements for $C_{stat_{rest}}$, $C_{stat_{1\ min}}$, and $C_{stat_{3\ min}}$ (5.63 ± 0.52 , 5.64 ± 0.55 , and 5.56 ± 0.54 L, respectively).

Discussion

This controlled study for the first time characterized the whole respiratory mechanical and muscle function of experienced male competitive BHD. We could confirm recent

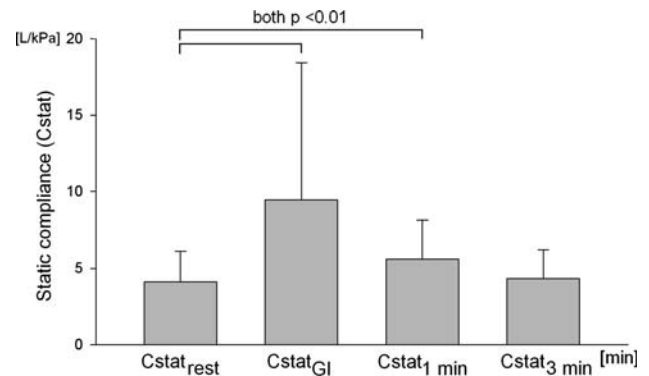


Fig. 1 Mean (SD) static lung compliance in the time course before and following a GI maneuver. $C_{stat_{rest}}$ static compliance measured from total lung capacity at rest; $C_{stat_{GI}}$ static compliance during the glossopharyngeal insufflation (GI); $C_{stat_{1\ min}}$ static compliance measured from total lung capacity 1 min after the GI maneuver; $C_{stat_{3\ min}}$ static compliance measured from total lung capacity 3 min after the GI maneuver; *min* minutes

findings that elite BHD have large dynamic lung volumes (Lindholm and Nyren 2005; Overgaard et al. 2006; Secombe et al. 2006) but could also show that this particular group of elite athletes did not differ significantly from healthy scuba divers or non-diving controls in terms of ventilatory flows or volumes. No pattern indicative of obstructive airway changes or lung hyperinflation in BHD could be discerned by pulmonary function testing. The diminished ratio of FEV_1/FVC that we obtained in BHD compared to both scuba divers and controls has not been reported so far. However, the mean value still was within the normal range. Yet two BHD had a FEV_1/FVC ratio of less than 70% that might indicate obstructive airway disease. Low FEV_1/FVC ratios have previously been reported from commercial divers working in the North Sea and were attributed to the extraordinarily large lungs found in these divers (Crosbie et al. 1979). In fact our BHD had very high VC values. Should obstructive airway changes arise from this particular exposure we would have expected to detect them in our BHD who had practiced apnea diving training including GI for more than five years on average. Thus it seems unlikely that glossopharyngeal insufflation may cause permanent lung hyperinflation when being performed repeatedly in the long-term. The relatively small sample size, however, may limit the conclusions on long-term changes to the ventilatory or mechanical parameters investigated.

In contrast to both scuba divers and non-diving controls there was a blunted response to CO₂ in the BHD group. This phenomenon has previously been described in commercial female South-Korean BHD (Song et al. 1963) and was explained by an adaptation to the repeated exposure to high CO₂ tensions during the repeated short (up to 90 s) breath-hold dives. Grassi et al. (1994) subsequently confirmed a blunted ventilatory response to CO₂ in three elite BHD who

were all members of the same family. The authors speculated that the high CO₂ tolerance may represent an adaptive or genetically inherited phenomenon. A limitation of the present study is the lack of a hypoxic ventilatory response test to further clarify the findings of the CO₂ response testing. This could be subject of further investigations.

This study also investigated respiratory muscle function in order to detect respiratory muscle affection in BHD, which may develop because of permanent strenuous respiratory muscle training from diving and certain breathing maneuvers. Moreover, chronic obstructive lung function changes due to repeated exposure to GI may be accompanied by respiratory muscle dysfunction, as pointed out above (Crosbie et al. 1979). BHD perform numerous GI maneuvers especially during training periods each day. Such, even though transient, drastic changes in lung volume might also alter the chest shape and therefore the working angles of respiratory muscles, such as in patients with chronic obstructive lung disease breathing at the same elevated lung volumes. P_Imax was used as a volitional measure for global respiratory muscle strength. Twitch mouth pressure was measured to assess diaphragmatic muscle strength more accurately and independent of the subject's effort. However, in the present study all subjects had normal respiratory muscle force with no significant differences between groups. Thus, the likelihood that chronic GI performance causes respiratory muscle affection in BHD seems to be negligible. Also a strengthening effect on the respiratory muscles function due to exhaustive and repeated use could not be detected.

Measurement of transpulmonary pressure and static lung compliance during GI has only been reported in one single diver from Australia (Simpson et al. 2003) and in a recent study of four elite BHD (Loring et al. 2007). In the latter study, the authors reported high transpulmonary pressures of 43–80 cmH₂O in three males and one female that were associated with increases in lung gas volume by 0.59–4.16 L at GI_{max}. In contrast, Simpson et al. (2003) did not find an elevated transpulmonary pressure in a single diver who increased his lung volume by 1.74 L upon GI. This result was subject to critique however because of a possibly improper measurement technique (Loring et al. 2007). The question if transpulmonary pressure increases following GI is clinically important in terms of divers' safety. Any elevation in transpulmonary pressure beyond a certain threshold, e.g. 30 cmH₂O, would increase the risk of lung barotrauma. In fact, Jacobsen et al. (2006) could recently demonstrate a pneumomediastinum by computed chest tomography (CT) in one of their subjects after performing GI. Remarkably, yet there are no other published reports about GI related pulmonary complications even though competitive breath-hold diving with GI is now frequently performed by athletes all over the world.

In this study, we were interested to measure lung compliance using the esophageal balloon technique in order to evaluate differences in lung mechanical properties between TLC in the normal state and at different points in time after GI_{max}. In eight males we could confirm a substantial increase in lung volumes of 1.75 (0.85) L on average by the GI technique that matches to previous studies (Lindholm and Nyren 2005; Overgaard et al. 2006). However, the important new finding of the present study was a transient alteration of lung elastic recoil as demonstrated by a subsequent decrease of static lung compliance over 3 min after GI. In five subjects who consented to attend the clinics for subsequent measurements we were able to demonstrate that static lung compliance remained elevated one and 3 min after GI and after subjects had exhaled and returned to normal tidal breathing. The increase of C_{stat} over baseline (C_{stat_{rest}}) was statistically significant for C_{stat_{GI}} and C_{stat_{1 min}}. C_{stat_{3 min}} values remained elevated above C_{stat_{rest}} but did not statistically significantly differ from baseline. These findings support the evidence that the GI maneuver is associated with a transient distention of the lung. Seccombe et al. (2006) calculated that only one third of the increase in measured lung volume by the GI maneuver was attributable to air compression thus the remainder is due to volume distension of the lung. In their study the authors reported that TLC measured within 5 min after GI was slightly but statistically significantly increased compared to TLC at baseline. In the current study we show that in fact there is a transient alteration in lung elastic recoil which is prolonged after filling the lungs to TLC after maximal glossopharyngeal insufflation.

It has been shown previously that lung elastic recoil pressure may be affected by breath holding. D'Angelo et al. (1993) demonstrated in healthy subjects that maximal expired flows and volumes were altered both by the speed of inspiration and by the preceding end-inspiratory breath hold. Lung elastic recoil also varies with lung volume. Rodarte et al. (1999) obtained a rapid decrease in lung recoil with voluntary increases in lung volume. These findings indicate that lung stretch may cause stress relaxation of airway wall tissues. Thus, we speculate that individual lungs that have the ability to over distend are those not being injured by over-distension when performing GI. Colebatch and Ng (1991) have shown previously that the lungs were less distensible in divers that experienced pulmonary barotrauma when compared to both healthy controls and divers who had an uneventful diving history. Remarkably, in the study of Loring et al. (2007) the one subject who showed a pneumomediastinum on CT had the lowest transpulmonary pressure at TLC and the smallest increase in FVC from TLC at GI. These findings may suggest that his lung distensibility could not meet the needs when insufflating air into the lung above TLC, possibly due to a lack of structural

adaptations. It is not clear, however, whether the decrease in lung elastic recoil at high lung volumes is due to a relaxation of contractile elements, e.g. lung elastic or collagen fibers, or to a change in surface forces by release of surfactant from alveolar type II cells. However, significant changes in surfactant release may not be expected to occur within a short time of 3 min only. This could be subject to further investigation.

In conclusion, lung function at rest did not reveal a pattern indicative of altered lung ventilatory or muscle function in experienced BHD who employ the GI technique frequently. Upon GI there was a statistically significant increase in both vital capacity and static lung compliance. The time course for static lung compliance recovery, however, was prolonged over a few minutes, indicating a transient alteration in lung elastic recoil.

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