Features of glossopharyngeal breathing in breath-hold divers

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Seccombe, Leigh M., Peter G. Rogers, Nghi Mai, Chris K. Wong, Leonard Kritharides, and Christine R. Jenkins. Features of glossopharyngeal breathing in breath-hold divers. J Appl Physiol 101: 799–801, 2006.—One technique employed by competitive breath-hold divers to increase diving depth is to hyperinflate the lungs with glossopharyngeal breathing (GPB). Our aim was to assess the relationship between measured volume and pressure changes due to GPB. Seven healthy male breath-hold divers, age 33 (8) [mean (SD)] years were recruited. Subjects performed baseline body plethysmography (TLCPRE). Plethysmography and mouth relaxation pressure were recorded immediately following a maximal GPB maneuver at total lung capacity (TLC) (TLCGPB), and within 5 min after the final GPB maneuver (TLCPOST). Mean TLC increased from TLCPRE to TLCGPB by 1.95 (0.66) liters and vital capacity (VC) by 1.92 (0.56) liters ($P < 0.0001$), with no change in residual volume. There was an increase in TLCPOST compared with TLCPRE of 0.16 liters (0.14) ($P < 0.02$). Mean mouth relaxation pressure at TLCPOST was 65 (19) cmH2O and was highly correlated with the percent increase in TLC ($R = 0.96$). Breath-hold divers achieve substantial increases in measured lung volumes using GPB primarily from increasing VC. Approximately one-third of the additional air was accommodated by air compression.

A community of competitive breath-hold divers, or freedivers, are attempting to set depth records as an extreme sport (12). These depth records have well surpassed early predictions based on theories of the maximum depth achievable by humans (6).

Looking for an advantage in a competitive sport, breath-hold divers have employed techniques that attempt to increase total lung capacity (TLC). This would allow for an increase in available O2 stores for breath holding and gas stores for pressure equalization while diving. Many breath-hold divers perform glossopharyngeal breathing (GPB) at TLC both as a training exercise and immediately before a dive. They breathe to TLC and perform GPB to increase the amount of air in the lungs (14). This technique has features in common with the maneuvers that have been reported to be used by postpolio (7, 9) and tetraplegic patients (5). Patients with severe neuromuscular weakness while retaining good bulbar muscle function have found this an effective alternative to ventilator use during the day by assisting lung ventilation.

There has been limited evidence of breath-hold divers increasing TLC using GPB (13, 14, 17). A recent study on five breath-hold divers using GPB reported a TLC increase of 25% (11) from changes in vital capacity (VC) measurements, assuming a constant residual volume (RV).

We hypothesize that the increase in measured lung volume due to GPB, as previously reported, is the result of increasing VC, with no effect on RV, and is primarily the result of gas compression. We wished to measure TLC acutely after cessation of GPB to confirm that the measured volume increase was primarily due to gas compression, with an immediate return to baseline levels.

METHODS

Subjects. Seven male competitive breath-hold divers who had previously practiced the technique of GPB were recruited. The subjects were nonasthmatic, were not current smokers, and did not have known or previous cardiac or lung disease.

Baseline “pre” lung function. Sitting spirometric tests and single breath transfer factor for carbon monoxide were measured to confirm normal lung function. Baseline body plethysmography (TLCPRE) (Sensormedics Vmax, Yorba Linda, CA) was then performed. All lung function tests were performed according to American Thoracic Society and American Association for Respiratory Care criteria (1, 3, 4) with predicted values derived from the recommendations of the European Community for Coal and Steel (8).

GPB plethysmography. Sitting body plethysmography was recorded immediately following a maximal GPB maneuver at TLC (TLCGPB). Once enclosed in the body plethysmograph, with tracing initiated by tidal volume, the subjects were instructed to come off the mouthpiece to perform the typical maneuver that allowed them to achieve what they believed to be their maximal lung volume with GPB, nose clip in situ. Then, without air leak, they returned to the mouthpiece and performed a slow expiratory VC maneuver to RV. Pairs against a closed shutter for thoracic gas volume (VTG) measurements were performed after a small inhalation (ERV2), immediately post-VC. This technique was replicated for TLCPRE and sitting plethysmography within 5 min of the final maneuver (TLCPOST). TLC was calculated by: TLC (VTGps) = VTG − ERV1 + VC.

If they usually performed “warm-up” stretching and GPB, we allowed time for them to do so after the baseline measurement (no more than 10 min).

Mouth relaxation pressure. The subjects were cognizant of the aims of measurement, and careful attention was given to obtaining open-glottis mouth relaxation pressure (Pmout). The pressure plateau was recorded at TLCGPB with a fluid-filled catheter inserted through pursed lips with no air leak. The catheter was connected to a physiological pressure transducer (Spacelab Program module, Spacelabs, Redmond, WA), and measurements were repeated until two maximal reproducible efforts (within 2 cmH2O) were obtained. The pressure transducer was calibrated by use of a water manometer and was zeroed at the level of the subject’s mouth before each measurement.

Because all lung volume measurements are performed assuming barometric pressure (Pbaro), the application of Boyle’s Law allowed us to estimate the compressive effect of the TLCGPB lung volume

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compared with the open-glottis TLCPRE lung volume. Any measured volume above TLCPRE that was not due to compression of air can be assumed to be causing distention of the lung (TLCDistended). Distention refers to the increased volume occupied by the lung in the hyperinflated and compressed state.

Boyle’s law states that for a mass of gas with temperature held constant the pressure (P) is inversely proportional to the volume (V). Therefore the pressure-volume product in compressed state (P1V1) equals the product in atmospheric state (P2V2) with constant body temperature. Thus:

\[(\text{absolute}) [P_{\text{Mouth}}] \times \text{TLCDistended} = P_{\text{Baro}} \times \text{TLCGBP}\]

Therefore,

\[
\text{TLCDistended} = \left( \frac{P_{\text{Baro}}}{P_{\text{Baro}} + P_{\text{Mouth}}} \right) \times \text{TLCGBP}
\]

The percent change in volume from TLCPRE values attributable to gas compression can then be estimated by

\[
\frac{\text{TLCGBP} - \text{TLCDistended}}{\text{TLCGBP} - \text{TLCPRE}} \times 100
\]

"Post" plethysmography. Sitting plethysmography was repeated within 5 min of the final GPB maneuver (TLCPOST).

All VTG curves and TLC, VC, and RV calculations were later verified by a second scientific officer who was not in attendance at testing. The body plethysmograph was calibrated before each testing session.

Supplemental O2, resuscitation equipment, and medical personnel were available at all times.

The study was reviewed, approved, and conducted in accordance with the principles of the World Medical Association Declaration of Helsinki 2000, and this included the provision of fully informed consent. The Ethics Committee was Central Sydney Area Health Service Human Research Ethics Committee (Concord Repatriation General Hospital zone).

Statistical analysis. Results were expressed as means (SD). A two-tailed repeated-measures ANOVA was performed to analyze the change in measured lung volumes from TLCPRE to TLCGBP and TLCPRE to TLCPOST. Significance was determined by use of a pairwise comparison and was considered significant if \(P < 0.02\). The relationship between mouth relaxation pressure at TLCGBP and change in measured lung volume, from TLCPRE to TLCGBP, was determined by use of a correlation analysis.

RESULTS

Seven male breath-hold divers were studied. The demographic and lung function data and breath-hold diving history of the study subjects are shown in Table 1. Baseline lung function in all subjects was within normal limits.

There were increases in intrathoracic gas volume from TLCPRE to TLCGBP, returned almost to resting values at TLCPOST, less than 5 min later. Mean percent increase in TLC from TLCPRE to TLCGBP was 24% (range 15–35) and in VC was 30% (range 22–44). Mean (SD) values for lung volume measurements and statistical significance are presented in Fig. 1.

Average measured mouth relaxation pressure at TLCGBP was 65 (19) cmH2O. The correlation of recorded mouth relaxation pressure at TLCGBP vs. the percent recorded volume change from TLCPRE to TLCGBP is shown in Fig. 2.

The mean increase in measured volume (from TLCPRE to TLCGBP) attributable to air compression was calculated as 31

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Table 1. Baseline lung function and diving history in 7 breath-hold divers

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD)</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>33 (8)</td>
<td>25–49</td>
</tr>
<tr>
<td>Height, cm</td>
<td>183 (7)</td>
<td>174–190</td>
</tr>
<tr>
<td>BMI</td>
<td>24.9 (2.0)</td>
<td>22.4–28.1</td>
</tr>
<tr>
<td>FEV1, % predicted</td>
<td>108 (18)</td>
<td>82–130</td>
</tr>
<tr>
<td>FVC, % predicted</td>
<td>120 (21)</td>
<td>89–149</td>
</tr>
<tr>
<td>TLCO, % predicted</td>
<td>100 (9)</td>
<td>88–113</td>
</tr>
<tr>
<td>Time breath-hold diving, yr</td>
<td>1.8 (1.3)</td>
<td>0.5–4.0</td>
</tr>
<tr>
<td>PB depth constant weight, m</td>
<td>47 (17)</td>
<td>32–80</td>
</tr>
<tr>
<td>PB static breath hold, min</td>
<td>5.47 (1:03)</td>
<td>4:20–7:02</td>
</tr>
</tbody>
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BMI, body mass index; FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; TLCO, single-breath lung carbon monoxide transfer factor; PB, personal best.
(3%). Hence, 69% of the change in measured lung volume is estimated to be attributable to distention of the lung.

The mean recorded increase in TLC from TLC\textsubscript{PRE} to TLC\textsubscript{GPB} was 1.95 liters (range 1.23–3.01). The mean volume due to air compression was 31% of this measured volume increase and equates to 610 ml (BTPS). Therefore, the mean increase in TLC that is distention of the lung is estimated to be 1.34 liters (BTPS).

**DISCUSSION**

This study has measured the substantial increases in lung volumes that breath-hold divers can achieve using GPB as described previously (13, 14, 17). This was primarily from an increase in measured VC, with no change in RV. From average recorded mouth relaxation pressure measured at TLC\textsubscript{GPB}, we estimate that 31% of the additional air was accommodated by air compression.

Conventionally TLC is the point of maximum inflation. This volume is reached when maximal inspiratory muscle tension is exerted. The increasing muscular disadvantage against an increasing chest wall and more importantly lung recoil is said to determine TLC (16).

To increase lung volume above normal TLC, GPB must overcome recoil pressures and distend the rapidly stiffening lung. This requires substantial pressure given the mouth relaxation pressures measured here range from 40 to 90 cmH\textsubscript{2}O. GPB above TLC is limited by “discomfort” and reported to improve with training (W. Steyn, personal communication). This raises the possibility that recoil pressure at high lung volumes may be altered transiently by lung overdistension. This view is consistent with our finding that TLC\textsubscript{POST} of all subjects measured in the 5-min period after GPB was increased outside expected normal intra-subject variation (1).

The concept of hysteresis explains the recoil pressure difference at a given lung volume depending on the volume history (i.e., during inflation or deflation) on a breath-by-breath basis (10). However, it is not inconceivable that, when lungs are distended by GPB beyond the normally obtained maximum inflation (i.e., TLC), the course time for lung and or chest wall recoil pressure recovery may be prolonged. Addressing this question, a previous report on a single elite breath-hold diver did not find a change in pulmonary compliance between normal and TLC\textsubscript{GPB}; however, they reported difficulty in measuring transpulmonary pressures during the GPB maneuver (17). Extrapolating the volume-pressure relationship of Rohrer and subsequent authors (2, 10, 15, 16) above 100% VC (equivalent to 50 cmH\textsubscript{2}O) suggests that the greater proportion of the increased mouth relaxation pressure measured here, averaging 65 (19) cmH\textsubscript{2}O, is generated by lung recoil pressure and a lesser proportion by chest wall recoil.

The measured volume increase was closely correlated with recorded mouth relaxation pressure in the TLC\textsubscript{GPB} state. The reporting of the volume reduction that occurs as a result of the air compression during relaxation against an obstruction is not new (2). From our subjects’ results, we estimated that this air compression accounted for only a 31% reduction of our measured volume increase from TLC\textsubscript{PRE} to the TLC\textsubscript{GPB} state. Thus 69%, or a mean of 1.34 liters (BTPS), we estimate to be due to the volume distension of the lung. The proportional distribution between the thorax and abdomen distention is yet to be determined and is subject to blood volume redistribution (11).

Methodology limitations resulted in the volume and mouth relaxation pressure measurements being recorded independently. Both measurements were highly reproducible. This small group of athletes represents a substantial portion of the competitive breath-hold divers nationally. Their results demonstrated consistent trends in all variables measured.

Our initial hypothesis that the measured increase in TLC due to GPB resulted primarily from an increased VC with no change in RV was supported. However, gas compression made a smaller contribution to this volume increase than we predicted. Importantly, we failed to support our hypothesis that there would be no difference between baseline TLC and that acutely after ceasing GPB. The elevated TLC once ceasing GPB suggests that there has been some transient distention of the lung.

**ACKNOWLEDGMENTS**

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**REFERENCES**