Features of glossopharyngeal breathing in breath-hold divers

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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. Pats against a closed shutter for thoracic gas volume (VTg) measurements were performed after a small inhalation (ERV1), 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 (TLP) = VTCO − 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 (Pmxmouth). The pressure plate 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 (Pbar), the application of Boyle’s Law allowed us to estimate the compressive effect of the TLCgpb lung volume by

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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).
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:

\[
\text{(absolute)}[P_{\text{Mouth}}] \times \text{TLC}_{\text{Distended}} = P_{\text{Baro}} \times \text{TLC}_{\text{GBP}}
\]

Therefore,

\[
\text{TLC}_{\text{Distended}} = \left( \frac{P_{\text{Baro}}}{P_{\text{Mouth}}} \right) \times \text{TLC}_{\text{GBP}}
\]

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

\[
\frac{\text{TLC}_{\text{GBP}} - \text{TLC}_{\text{Distended}}}{\text{TLC}_{\text{GBP}}} \times 100
\]

“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 Raptaration 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.

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

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

<table>
<thead>
<tr>
<th>Mean (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>33 (8)</td>
</tr>
<tr>
<td>Height, cm</td>
<td>183 (7)</td>
</tr>
<tr>
<td>BMI</td>
<td>24.9 (2.0)</td>
</tr>
<tr>
<td>FEV1, % predicted</td>
<td>108 (18)</td>
</tr>
<tr>
<td>FVC, % predicted</td>
<td>120 (21)</td>
</tr>
<tr>
<td>TLCO, % predicted</td>
<td>100 (9)</td>
</tr>
<tr>
<td>Time breath-hold diving, yr</td>
<td>1.8 (1.3)</td>
</tr>
<tr>
<td>PB depth constant weight, m</td>
<td>47 (17)</td>
</tr>
<tr>
<td>PB static breath hold, min:s</td>
<td>5:47 (1:03)</td>
</tr>
</tbody>
</table>

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.

![Fig. 1. Mean measured total lung capacity (TLC) with 1 SD bars, partitioned into vital capacity (VC) and residual volume (RV), in 7 breath-hold divers at baseline (TLCPRE) immediately following a maximal glossopharyngeal breathing maneuver at TLC (TLCGBP) and within 5 min of their final glossopharyngeal breathing maneuver (TLCPOST). *Compared with TLCPRE (P < 0.0001, repeated-measures ANOVA). **Compared with TLCPRE (P < 0.02, repeated-measures ANOVA).](http://jap.physiology.org/)

![Fig. 2. Plot of individual measurements (●) of mouth relaxation pressure at TLCGBP with the corresponding % change in measured volume from TLCPRE to TLCGBP. Solid line, correlation.](http://jap.physiology.org/)
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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.

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REFERENCES