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Evidence of respiratory system remodelling in a competitive freediver

To the Editor:

We present a healthy freediving subject with increasing lung volumes associated with repeated use of a technique used to enhance athletic performance. The repeated use of the technique over time appears to have altered respiratory system mechanics without any functionally important macroscopic lung damage, at least as evidenced by computed tomography scans and measures of gas exchange.

Glossopharyngeal insufflation (GI) employs the glossopharyngeal structures to force air into the lungs above total lung capacity (TLC). It was developed to assist patients with diaphragm weakness in the era when polio was common [1]. Competitive freedivers have modified this technique to increase lung gas prior to apnoea [2], which has proven to enhance duration, distance and depth achieved while submersed.

Lung barotrauma has been associated with GI [3, 4], which raises the possibility that use of this technique results in significant lung damage and long-term physiological impairment.

The research data from a healthy competitive freediver who practised regular GI training was reviewed. This included longitudinal respiratory function and computed tomography images.

On initial presentation in 2004, the subject was a 25-year-old male (186 cm, 90 kg), healthy with no known respiratory or cardiac disease and was not taking any medications. A recreational spearfisher since 1999, he had taken up freediving and regular GI training in 2002. Training sessions increased to three times weekly by 2009, a level that was maintained through to 2012 and he consistently competed at a national level. The subject's static apnoea performance (breath-hold time) had increased from 7 min in 2004 to 8 min in 2012 and there has been a 37 m increase in ocean depth achieved (unassisted with fins) to 88 m. He had been in good health in this period without proven barotrauma.

Complex respiratory function tests prior to, and immediately following, maximal GI were reviewed. Measurements were taken on four occasions over a period of 8 years (from age 25 to 33 years). All tests were performed according to American Thoracic Society/European Respiratory Society criteria [5–7] and were conducted by the same scientific officer with one equipment upgrade (Vmax Encore, Sensormedics, Yorba Linda, CA, USA). Lung volumes immediately following maximal GI (TLC_{GI}) were measured using a technique previously described [2]. Measurements were made using a plethysmograph, recording exhaled gas volumes rather than Euclidian (geometric) volumes, thus being free of a gas compression effect. Reference values were derived from European Community for Coal and Steel [8].

Previous studies of freedivers, spearfishers and swimmers have noted overall large lung volumes when compared to normal. This subject was no exception. In addition, he is adept at GI and was able to entrain an additional 2.4 L of gas achieving a vital capacity (VC) following GI equivalent to 192% of predicted in 2004. By 2012 the additional lung gas volume from GI had reduced to 1.62 L, in proportion to the increase in VC.

Over the review period, an increase in measured lung volumes is evident with a total >800 mL increase in VC, functional residual volume (FRC) and TLC (table 1). There is no evidence

TABLE 1 Lung volumes in a competitive freediver

	6 September, 2004	17 January, 2009	20 October, 2009	7 May, 2012
FEV_1 L (% pred)	6.20 (130)	5.87 (129)	6.18 (138)	6.28 (141)
VC L (% pred)	8.11 (142)	8.62 (158)	9.09 (166)	9.02 (167)
VC_{GI} L (% pred)	10.55 (192)	10.31 (188)	10.75 (197)	10.64 (188)
Per cent increase in VC with GI	30	20	18	18
TLC L (% pred)	10.08 (129)	10.60 (139)	10.56 (139)	10.87 (143)
TLC_{GI} L (% pred)	12.42 (159)	12.29 (161)	12.22 (161)	12.49 (164)
FRC L (% pred)	3.81 (109)	4.24 (121)	4.66 (133)	4.73 (134)
RV L (% pred)	1.87 (107)	1.98 (108)	1.47 (80)	1.85 (97)
$T_{L,CO}$ adj mmol·kPa^{-1}·min^{-1} (% pred)	13.5 (104)		11.7 (94)	12.7 (103)
K_{CO} adj mmol·kPa^{-1}·min^{-1} (% pred)	1.42 (66)		1.22 (58)	1.30 (63)

FEV_1: forced expiratory volume in 1 s; % pred: % predicted; VC: vital capacity; GI: glossopharyngeal insufflation; TLC: total lung capacity; FRC: function residual capacity; RV: residual volume; $T_{L,CO}$ adj: transfer factor for carbon monoxide adjusted for haemoglobin; K_{CO}: $T_{L,CO}$ corrected for alveolar volume.

of gas trapping as residual volume (RV) remains unchanged and transfer factor for carbon monoxide ($T_{L,CO}$) and $T_{L,CO}$ corrected for alveolar volume (K_{CO}) are preserved. The subject is adept at GI but there is an observed limit to TLC_{GI} despite ongoing GI training.

The increase in VC, FRC and TLC over time can be explained by a reduction in chest wall recoil at higher lung volumes as a consequence of repeated GI. In the absence of more complex transpulmonary pressure measurements, this does not discount a possible contribution of changes in the lung itself. A reduction in lung elastic recoil is often accompanied by an elevated RV, which was not evident here. This is in keeping with the observations of WALTERSPACHER *et al.* [9] who found no change in dynamic or static compliance in four freedivers after 3 years of GI participation. NYGREN-BONNIER *et al.* [10] demonstrated small increases in VC in healthy normals following 6 weeks of GI training, also with no change in RV.

Interestingly, TLC_{GI} has remained stable. Whether this is due to the inability of the lung to expand further irrespective of the behaviour of the chest wall, or to an intrinsic limit imposed by the chest wall is not known. The stable $T_{L,CO}$ and K_{CO} are consistent with no effect on the pulmonary capillary blood volume. Despite a limit to TLC_{GI}, performance has improved suggesting the importance of additional training attributes.

Non-contrast computed tomography images of the thorax, previously acquired in 2009, were also reviewed and segmented for three-dimensional analysis of lung tissue. Images were captured during breath-hold (~80 s) at TLC_{GI} and during tidal breathing. Lung tissue was segmented from the computed tomography images, volumes calculated (ITK-SNAP, University of Pennsylvania, PA, USA.) then rendered in three dimensions (Blender 2.63a, the Netherlands).

The significantly increased lung volumes seen on the TLC_{GI} image reflects the great mechanical force on the respiratory system with GI. There is intercostal bulging of lung tissue, mediastinal distortion and flattening of the diaphragm.

Longitudinal monitoring of a competitive freediver spanning this time period has not been previously presented. As demonstrated in this case, repeated exertion of the great force that GI imposes on the respiratory system can alter its mechanics. This has been achieved without developing functionally important lung damage, at least as evidenced by the computed tomography scan and measures of gas exchange. Whether long-term use of this technique might create a performance advantage in sports that do not require apnoea is a matter for speculation.

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