

Determination Of Lung Volumes Using Spiral CT During Glossopharyngeal Insufflation

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Abstract

Glossopharyngeal insufflation (GI, 'lung packing') enables experienced freedivers to voluntarily increase the intrapulmonary gas volume beyond the normal total lung capacity (TLC). The precise, individual quantification of this additional volume is important for training management, risk assessment and the diagnosis of GI-associated complications. Spiral computed tomography (spiral CT) with three-dimensional volumetric segmentation represents a validated, non-invasive method for this purpose; it is already established in diagnostics and can be methodologically adapted to determine the GI-induced additional volume. This study presents the physiological principles of GI, the current state of the art in spiral CT-based lung volumetry, and a detailed investigation of 30 freedivers, with the aim of quantifying GI-induced volume changes using CT volumetry, correlating these with spirometric reference values, and enabling conclusions to be drawn regarding the benefits for competitive freediving.

Keywords: Glossopharyngeal Insufflation, Lung Packing, Freediving, Spiral Ct, Helical Ct, Lung Volumetry, Total Lung Capacity

Introduction

Glossopharyngeal insufflation is used by experienced competitive freedivers to pump additional volumes of air into the lungs via rhythmic movements of the tongue and pharynx, thereby increasing the initial volume prior to the dive beyond the individual's TLC [2][6]. This increase in volume can amount to up to 50 per cent of vital capacity [6] and is associated with a rise in transpulmonary pressure as

well as an increased risk of cardiovascular and pulmonary complications [1][8]. To date, GI-induced additional volume has predominantly been estimated in the literature using spirometry or plethysmography, or documented selectively via CT in individual physiological studies [8]. A systematic CT-volumetric quantification validated on a larger group of divers is currently lacking.

Spiral CT enables three-dimensional segmentation of the lung parenchyma through continuous volume acquisition during a single breath-hold scan, thereby allowing for automated, reproducible volume measurement^{[19][17]}. In diagnostics, this method for quantifying lung volumes is methodologically established and has been validated against reference values from pulmonary function testing^{[16][18]}. The aim of this study is to conceptually apply this established methodology to the question of GI-induced volume increase in apnoe divers.

The physiological principles of glossopharyngeal insufflation involve the oral cavity being filled with air following maximum inspiration whilst the glottis is closed; this air is then forced into the lungs by opening the glottis and contracting the tongue and pharyngeal muscles, before the glottis is closed again. This cycle is repeated several times, during which intrapulmonary pressures of around 100 mbar can be reached^[6]. Longitudinal studies also suggest that regular diving leads to training-induced remodelling of the respiratory system, with an increase in vital capacity and total lung capacity (TLC)^[2], which underlines the need for individual, reproducible volume measurement, for example using CT.

The technical principle of a spiral CT is based on continuous X-ray tube rotation combined with simultaneous, constant table advancement, thereby enabling a complete volume data set of the thorax to be acquired within a single breath-hold manoeuvre^[19]. Compared with sequential CT, this enables a reconstruction with fewer motion artefacts and greater overlap, and thus more precise detection of small pulmonary volumes as well as more reliable volumetric post-processing^[19]. For automated lung volumetry, the parenchyma is segmented on the basis of density thresholds (Hounsfield units, HU). Established protocols use lower thresholds of around -1024 HU and upper thresholds between approximately -200 and -900 HU, with three-dimensional methods tending to yield slightly higher but more reproducible volumes compared with two-dimensional approaches^[18]. For inspiratory scans, an upper threshold of around -200 HU is described as robust for TLC determination^[18], whilst different thresholds are used for expiratory scans.

Several studies have demonstrated a good correlation between TLC determined volumetrically by CT and TLC measured by plethysmography, although inspiratory CT measurements may underestimate TLC by an average of around 12 per cent, whilst the overall correlation remains good ($r \approx 0.89$)^[18]. Quantification using low-dose spiral CT also correlated significantly with conventionally dosed protocols and with lung function parameters, whilst simultaneously offering significantly reduced radiation exposure^[16]. This preliminary methodological work from general pulmonology formed the basis for applying the method to the specific issue of GI-induced volume increase.

Methodology

Objectives and Hypotheses

The primary aim of the study design was to quantify GI-

induced pulmonary volume increase using spiral CT volumetry in 30 experienced freedivers and to compare this measurement with reference values obtained via spirometry and plethysmography.

A single-centre, prospective observational study with a pre-post comparison (baseline CT without GI versus CT immediately after the GI manoeuvre) was chosen as the study design. The sample comprised 30 experienced freedivers who reported practising GI regularly.

Inclusion criteria were an age between 18 and 50 years, active competitive or advanced recreational freediving, medical fitness for freediving, and written informed consent.

Exclusion criteria included known structural lung disease, previous thoracic surgery, pregnancy, contraindications to X-ray exposure in accordance with the ALARA principle, and acute respiratory symptoms.

The study required approval from the relevant ethics committee (HKBS 2021-00-30/60) and justification of the indication in accordance with national radiation protection legislation.

Following informed consent and inclusion, a whole-body plethysmography scan was first performed to determine the individual TLC, along with a diffusion capacity measurement in accordance with current standardisation recommendations. Subsequently, an initial spiral CT scan of the thorax was performed during deep inspiration without GI (baseline). After a rest period, each subject performed a standardised GI manoeuvre under medical supervision up to their subjective maximum packing capacity, immediately followed by a second spiral CT scan using the breath-hold technique. As the GI manoeuvre itself was associated with a documented risk of syncope, arrhythmias and pulmonary barotrauma^{[1][14][7]}, the GI manoeuvre was to be carried out as part of the study protocol under medical supervision, with immediate resuscitation facilities available. To minimise radiation exposure, low-dose protocols were used, as these have been shown to provide diagnostic accuracy comparable to that of standard-dose protocols, whilst reducing the radiation dose^[16]. Against this background, limiting the number of CT scans to two per subject (baseline and post-GI) appears justified. A multi-slice spiral CT (multidetector CT) was used. The scans were performed with a thin slice thickness (≤ 1.5 mm) using overlapping reconstruction for 3D segmentation. We selected a lower segmentation threshold of -1024 HU and an upper threshold range of -200 to -900 HU, in line with published validation studies.

Results

Descriptive analysis was performed as the mean $\pm$ standard deviation. The comparison of CT-volumetric TLC before and after GI was carried out using a paired t-test. The agreement between CT volumetry and spirometry was assessed using Pearson's correlation. A two-tailed significance level of $\alpha = 0.05$ was used.

Competition diving data were recorded within the apnoea disciplines. STAT referred to static apnoea diving, defined as the maximum breath-hold time whilst the head is submerged. DYN stood for dynamic diving, which was defined as the maximum horizontal distance covered underwater without

fins (Dynamic Apnoea without Fins – DNF). The average diving depth was used to indicate the vertical distance covered in the water without fins (Constant- weight, no fins – CNF). Table 1 summarises the descriptive data for the study group.

Table 1: Descriptive data for the freedivers studied (n=30)

	Freedivers (n=30)	
	Mean	SD
Age (years)	47.9	11.9
Gender (1=m; 2=f)	1.3	0.5
Height (cm)	177.4	7.7
Weight (kg)	74.4	15.0
Diving depth – CNF (m)	38.9	18.0
STAT (min)	05:03:51	01:02:17
DYN-DNF (m)	110.0	31.9

We use body plethysmography to determine total lung capacity (TLC). The measurement records the total intrathoracic gas volume. This also includes non-

communicating or very slowly ventilated compartments. Table 2 shows the results of the study for the 30 freedivers, presented as mean and standard deviation.

Table 2: Body plethysmography

	Freedivers (n=30)	
	Mean	SD
TLC (l)	7.46	1.32
FRC (l)	3.93	0.86
RV (l)	2.34	0.68
FRC + RV (l)	6.27	1.40
VCmax (l)	5.12	1.13
FVC (l)	4.98	1.13
FEV1 (l)	3.82	0.92
FEV1%VCmax (%)	74.35	5.81
PEF (l/s)	8.25	2.20

Table 3 shows the results of the diffusion capacity measurement. The diffusion test measured only the volume that mixed with the inhaled test gas during the brief breath-hold period and therefore concerned only the communicating,

well-ventilated lung tissue. The difference in volume between body plethysmography and the diffusion capacity test averaged 430 ± 160 ml, in favour of plethysmography.

Table 3: Diffusion capacities

	Freedivers (n=30)	
	Mean	SD
DLCO (mmol/(min*kPa))	8.93	2.26
KCO (mmol/(min*kPa))	1.30	0.21
VA (l)	6.83	1.17
TLC (l)	6.99	1.19
FRC (l)	3.57	0.94
RV (l)	2.19	0.14

Table 4 shows the lung volume parameters calculated from the CT scan. The average volume measurements for both sides of the lungs corresponded to the total lung capacity following glossopharyngeal insufflation.

Table 4: Average lung volumes on CT following GI

	Freedivers (n=30)	
	Mean	SD
Both lungs (ml)	7349.56	1529.28
Right lung (ml)	3,915.90	787.84
Right upper lobe (ml)	1,460.51	253.85
Right middle lobe (ml)	543.33	171.00
Right lower lobe (ml)	1911.37	460.70
Left lung (ml)	3,461.25	727.92
Li upper lobe (ml)	1,609.50	349.35
Li lower lobe (ml)	1,754.79	419.33

Table 5 shows the target values intended for the analysis. The additional volume induced by GI in the supine position differed by 111 ± 210 ml from body plethysmography and by 449 ± 340 ml from diffusion capacity.

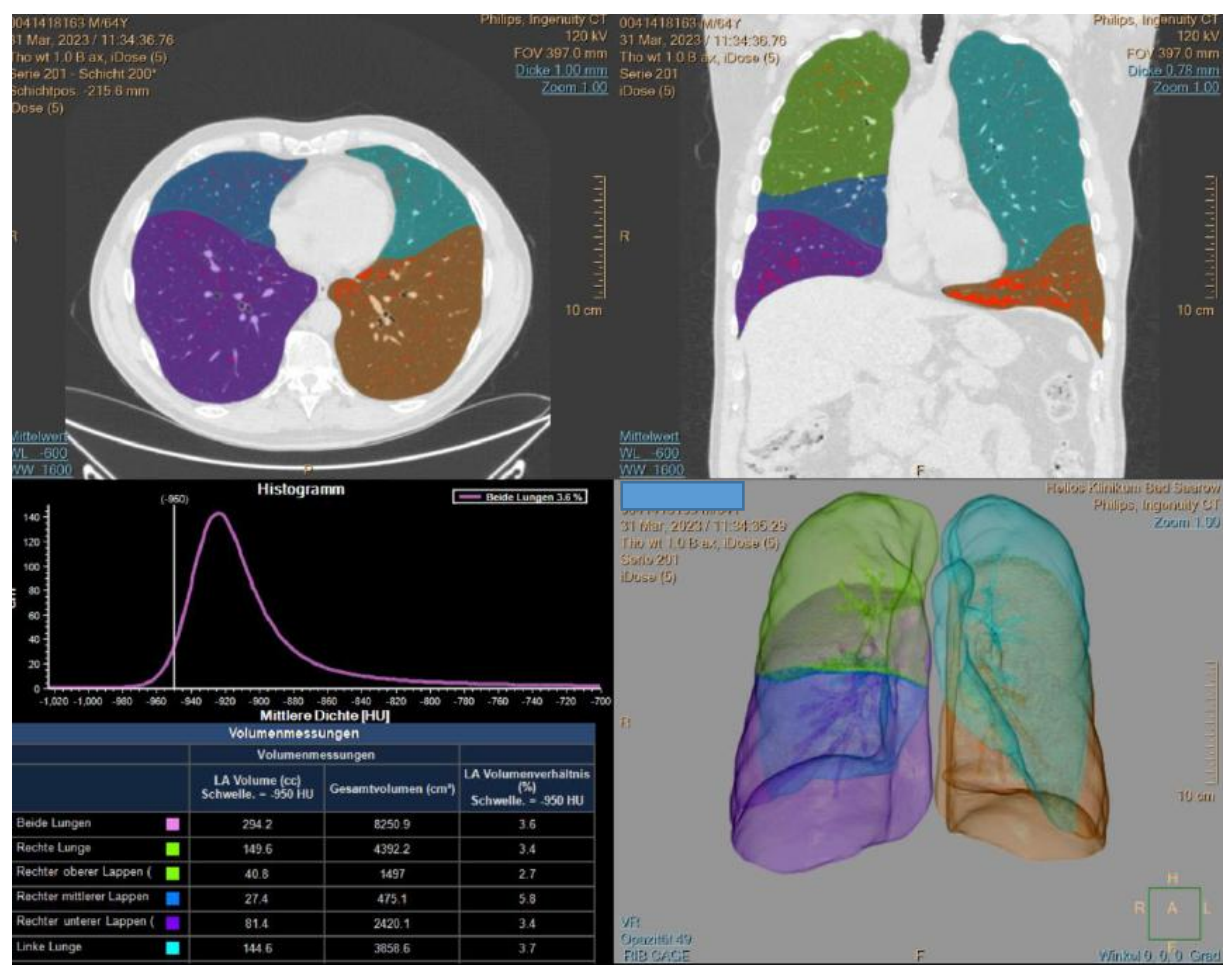
Parameter	Method	Result
TLC without GI (baseline)	Plethysmography; Diffusion	7.46 ± 1.32 L vs 6.99 ± 1.19 L $p > 0.05$
TLC with GI (post-packing)	Spiral CT, breath-hold scan following GI manoeuvre, average change	7349 ± 1530 ml
TLC with GI (post-packing)	Spiral CT, breath-hold scan following GI manoeuvre, positive change	8162.7 ± 1287.8 ml
GI-induced additional volume (ΔV)	CT volumetric difference: TLC(GI) – TLC(Baseline), average change	Pre: 7528.1 ± 1320 ml Post: 7588.5 ± 1474 ml $\Delta V = 60 \pm 797.6$ ml $p > 0.05$
GI-induced additional volume (ΔV)	CT-volumetric difference: TLC(GI) – TLC(Baseline) positive change	Pre: 7528.1 ± 1320 ml Post: 8162.7 ± 1288 ml $\Delta V = 635 \pm 1304$ ml $p < 0.05$

Correlation between CT volumetry and plethysmography; diffusion	Pearson's correlation	Body vs CT $P=0.058$ Diff vs CT $P = -0.157$
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Table 1: Planned target parameters of the proposed study protocol (n = 30, placeholder representation without actual results data).

Figure 1 shows, in addition to the colour-coded CT sagittal sections and the horizontal colour delineation of the lung areas based on the lung fissures, the lung volumes calculated on the basis of the mean HU density and the multidimensional, reconstructed lung image.

Figure 1: Spectral analysis of the lungs using CT (example)



If, for the GI manoeuvres in the supine position on CT, only those measurements were taken into account in which a positive dynamic change (positive packing) relative to the body plethysmography was observed compared with the CT pre-scan, 12 of the 30 freediving measurements—with an average volume change of -494.0 ± 830.6 ml—had to be disregarded. In the group showing positive dynamics in the change in lung volume, there was an increase of 530.5 ± 408.1 ml ($p<0.05$). The change relative to the pre-scan CT in this group was 635 ± 1304 ml following GI ($p<0.05$).

When the positive volume changes due to GI were correlated with the dive depth (CNF), a Pearson correlation coefficient of $P = 0.075$ was obtained. A Pearson correlation coefficient

of $P = 0.134$ was obtained for the STAT apnoea time. When the correlation between the volume changes due to GI and the dynamic dive distance (DYN-DNF) was examined, a value of $P = 0.73$ was obtained.

Discussion

The CT-volumetric TLC measurement was subject to a methodologically induced underestimation compared with the plethysmographic reference values, as the measurement was limited to a single point in time immediately following the GI manoeuvre. In body plethysmography, the lung volume determined before GI was 100 ml higher than the volume determined by CT after GI. The discrepancy between the plethysmographic measurement and the total lung

capacity measured in the diffusion capacity test (single-breath method with carbon monoxide dilution) is essentially due to a methodological difference. Plethysmography measured the total intrathoracic gas volume, including non-communicating or very slowly ventilated compartments. By contrast, the gas dilution method used in the diffusion test measured the volume that mixed with the inhaled test gas during the brief breath-hold period (approx. 10 seconds), i.e. only the communicating, well-ventilated lung tissue. The difference in TLC between the two examination methods was 430 ml, in favour of plethysmography. The Pearson correlation between diffusion capacity measurement and the GI volumes obtained on CT was $P = 0.15$. The difference between the CT volume calculation based on GI and the diffusion test results was 450 ml lower.

In well-trained freedivers, we observed an effective and positive increase in volume due to GI during CT of 530 ml on average, and an individual increase in lung volume between the pre- and post-scan of 635 ml. These results were reflected in the competition results of the freedivers only in the horizontal dive distance ($P = 0.84$). No correlation with dive depth or static apnea duration could be established based on the increases in lung volume due to GI.

It is therefore significant whether a glossopharyngeal insufflation is mastered by freedivers, or whether attempts at glossopharyngeal insufflation result in no significant increase in lung volume. A meaningful prognosis can be derived from the physiological assessment of functional residual capacity and diffusion capacity. It appears that diaphragmatic dynamisation plays a decisive role in this regard.

Conclusion

Spiral CT is a methodologically suitable, validated procedure for the non-invasive, three-dimensional quantification of lung volumes and can be conceptually applied to the issue of glossopharyngeal insufflation in freedivers. The results presented from the study of 30 freedivers provided a structured methodological framework for objectively quantifying the GI-induced additional volume and validating it against spirometric reference values.

The effectiveness of glossopharyngeal insufflation in the freedivers studied showed considerable variability, ranging from -2,903 ml to +1,324 ml on the spiral CT scan following GI. If only those freedivers with GI were considered, in whom a positive trend was observed between the pre-scan CT and the determination of total lung capacity via diffusion capacity measurement, the increase in lung volume ranged from 79 ml to 1,324 ml.

Based on the competition results, the increase in lung volume was reflected only in the increase in horizontal diving distance (DYN-DNF) without fins.

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