

Evaluation Of Different Pulmonary Function Diagnostic Methods For Predicting The Maximum Depth Of Apnoeic Diving

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Abstract

Background: The maximum depth achievable in freediving is limited by a combination of pulmonary, cardiovascular and technical factors. As the lungs, being a compressible reservoir of respiratory volume, are directly subject to the increase in hydrostatic pressure, pulmonary function testing is considered to play a central role in assessing an individual's depth capacity and the risk of injury ('lung squeeze').

Objective: This review compares common pulmonary function tests in terms of their predictive value for maximum freediving depth and compares the results with those from freedivers and SCUBA divers. The aim was to analyse functional, structural and exercise-physiological differences between 30 AIDA competitive freedivers and 30 experienced SCUBA divers.

Methodology: A literature review was conducted in PubMed, Frontiers, Springer Link and other databases on the physiological determinants of apnoe diving depth. In a cross-sectional analysis, various medical measurement methods, including spirometry, body plethysmography and DLCO (diffusion capacity) measurement, were employed and compared with the average diving depth achieved.

Results: The ratio of residual volume to total lung capacity (RV/TLC) has a theoretical, mathematical relationship with the depth limit, whilst spirometry parameters were also found to be useful, offering a higher probability of prediction. Freedivers exhibited significantly higher total lung capacities (TLC) and functional residual capacities (FRC) than SCUBA divers. DLCO was significantly elevated in freedivers, suggesting an increased alveolar-capillary exchange surface area.

Diffusion capacity measurement provided the highest predictive value for the average dive depth achieved by 30 AIDA freedivers.

Conclusion: As a single test, diffusion capacity measurement allows for a reliable individual prediction of maximum apnoe diving depth.

Keywords: Freediving, Lung Function, Residual Volume, Body Plethysmography, Glossopharyngeal Insufflation, Lung Squeeze, Diving Depth.

Introduction

Apnoe diving (freediving) has evolved from a traditional livelihood – such as that of the Ama divers of Japan or the so-called ‘Ocean Nomads’ of South-East Asia – into an internationally organised competitive sport with clearly defined depth, time and distance disciplines. The documented depth records have continued to improve: from the anecdote about Giorgios Statti, who allegedly reached 70 m in 1913, through to the first breaking of the 100-metre mark by Jacques Mayol in 1976, and on to Herbert Nitsch’s official world record of 214 m in 2007 [1].

This development raises a key physiological question: which physical characteristics – in particular, which lung function characteristics – enable such extreme depths, and can these characteristics be assessed diagnostically to predict an individual’s maximum diving depth or to estimate the risk of pressure-related lung damage (‘lung squeeze’, pulmonary barotrauma) [2, 3]?

In contrast to maximum apnoea time, which is primarily determined by oxygen storage capacity, metabolic economy and hypoxia tolerance, maximum diving depth also depends on the mechanical properties of the thoracic-lung system, as the intrathoracic gas volume is compressed with increasing depth in accordance with Boyle–Mariotte’s law [4].

This study provides a structured overview of the available pulmonary function diagnostic methods and evaluates their respective predictive value for maximum diving depth; it is supported by practical data from sports medicine examinations of 30 AIDA freedivers and 30 SCUBA divers.

Physiological principles of depth limitation

During descent, the ambient pressure increases by approximately 1 atmosphere (ATA) for every 10 metres of water depth. As the lungs – unlike those of many marine mammals – cannot collapse completely, the intrapulmonary gas is compressed, whilst at the same time blood is shifted from the body’s periphery into the thorax (‘thoracic blood shift’), making it difficult to fall below the effective residual volume [1, 5].

Mathematically, assuming a constant thoracic blood shift, a theoretical depth limit can be derived from the ratio of residual volume (RV) to total lung capacity (TLC). By way of illustration, a calculated depth limit of approximately 49 m was determined for an elite diver with an RV of 1.7 l and a TLC of 10 l. Taking into account an assumed thoracic blood shift of 1000 ml, this limit shifts to around 134 m, as the effective RV falls to 0.7 l. By assuming an increase in TLC to 13.2 l via glossopharyngeal insufflation (GI), a calculated depth of 179 m was achieved; with additional glossopharyngeal exsufflation (GE) reducing the residual volume to 0.4 l, calculated depths of around 320 m were

even attained [6]. This example calculation illustrates why lung volumes and their voluntary modification are central to pulmonary function testing.

In addition to sheer volume capacity, the compliance of the thoracic-pulmonary system, the efficiency of gas exchange under pressurised conditions, and the individual’s ability to perform pressure equalisation techniques all play a role in determining the depth that can actually be reached and safely tolerated [7, 8].

Lung sonography (B-lines), cross-sectional imaging (CT), thoracic and pulmonary compliance, and glossopharyngeal insufflation/exsufflation as a functional test

Lung sonography with quantification of so-called B-lines (‘ultrasound lung comets’) is regarded as a valid, non-invasive marker of extravascular lung water. In a study of 40 competitive divers, the B-line score correlated negatively with the minimum and mean arterial oxygen saturation following the dive [20], and in several studies, the B-line score increased with increasing dive depth [15]. The method is suitable for field use and is now recommended in safety protocols by competition organisers [21].

Chest CT and MRI allow for precise volumetry and have been used to investigate glossopharyngeal manoeuvres [17]. However, due to their lack of suitability for field use, these procedures remain restricted to scientific research and the investigation of incidents [22].

The measurement of lung or thoracic compliance, usually using the oesophageal balloon technique to estimate transpulmonary pressure, allows for a direct assessment of the system’s elastic distensibility. In elite freedivers, following glossopharyngeal insufflation, a transient decrease in elastic recoil was demonstrated, accompanied by a consequent increase in compliance, which remained detectable for up to several minutes after insufflation [14]. Higher compliance could theoretically allow for greater volume reduction without tissue damage and thus indirectly make greater depths tolerable. However, this procedure is invasive, complex and has so far only been used in a few research settings involving elite athletes, meaning that no broad normative data set exists [2, 15].

Glossopharyngeal insufflation (GI), a pumping-like manoeuvre involving the tongue, pharynx and larynx, enables trained divers to increase their lung volume by several millilitres and litres beyond the spirometrically measured TLC. Conversely, glossopharyngeal exsufflation (GE) reduces the residual volume (RV) below the physiological RV to enable pressure equalisation at greater depths [16]. As both techniques directly alter the individual’s maximum achievable volume, their quantification can be understood as

a 'functional depth test' that goes beyond static pulmonary function testing. However, GI and GE are associated with significant risks. The increase in intrapulmonary pressure during GI could reach up to 80 cmH₂O and has been linked to right ventricular pressure overload, left ventricular dysfunction, pneumothorax and arterial gas embolism [18, 19]. These procedures are therefore primarily relevant in elite sport and under expert supervision, and are not readily suitable as a general diagnostic screening tool.

Supplementary non-pulmonary parameters

For the sake of completeness, it should be noted that, in addition to pulmonary parameters, peripheral oxygen saturation, spleen volume and body composition have also been repeatedly associated with apnoea performance [11, 23]. However, these parameters are not strictly of a pulmonary diagnostic nature and are mentioned here solely for the sake of clarification, as a prediction of diving depth must always be made within the overall context of cardiovascular, haematological and technical factors [24].

Methodology

First, a narrative, non-systematic literature search was carried out in PubMed, Frontiers in Physiology, the Journal of Applied Physiology, Springer Link and other freely accessible sources. Search terms included, amongst others, 'breath-hold diving', 'freediving', 'pulmonary function', 'residual volume', 'glossopharyngeal insufflation', 'lung squeeze' and 'maximum diving depth'. Original studies and review articles relating to pulmonary functional determinants of apnoeic diving performance were included. Due to the limited number of controlled studies involving elite divers, this work takes the form of a narrative review rather than a systematic review as defined by PRISMA.

Furthermore, in a comparative cross-sectional analysis, we examined trained Apnoe International Diving Association (AIDA) freedivers and experienced Self-Contained Underwater Breathing Apparatus (SCUBA) divers. In each group, following information provision, consent and written authorisation for the study, as well as approval from the regional ethics committee (HKBS 2021-00-30/60), there were 30 volunteer AIDA freedivers and 30 volunteer SCUBA divers. The study included healthy AIDA freediving competitive freedivers with more than 3 years' freediving training and experienced SCUBA divers with more than 300 active dives.

Data on maximum dive depth, static apnea times and dynamic apnea distance were collected from competition records, training logs and personal records.

An overview of pulmonary function diagnostic procedures

Spirometry

Spirometry measures dynamic and static exhalation parameters such as forced vital capacity (FVC), forced expiratory volume in the first second (FEV1) and the FEV1/FVC ratio. It is regarded as the standard procedure in

pulmonary function testing; it is suitable for field use, cost-effective and non-invasive [9, 10]. In elite divers, compared with untrained control subjects, repeatedly increased vital capacities have been described, as well as FEV1/FVC ratios varying on average between 0.67 and 0.94—in some cases reduced—which suggests a training-induced change in the airway and thoracic profile [3].

In a study of 36 male freedivers, lung capacity correlated positively with maximum static apnoea time, whilst body mass index and body fat percentage correlated negatively [11]. However, these correlations primarily relate to apnoea time, not directly to diving depth – an important conceptual distinction, as both performance parameters are subject to different physiological limits. Spirometry therefore provides a useful indicative baseline value, but does not offer a direct prediction of depth.

Body plethysmography: static lung volumes and RV/TLC ratio

In contrast to spirometry, whole-body plethysmography allows the determination of residual volume (RV) and total lung capacity (TLC), including the non-expirable gas fraction. In the literature, the RV/TLC ratio is regarded as the parameter with the strongest direct, mathematically verifiable relationship to the theoretical depth limit, as it directly determines the ambient pressure at which the intrathoracic gas volume would be compressed below the critical residual volume [6, 12].

However, the RV/TLC ratio is insufficient as a standalone predictor, as it does not account for dynamic compensation through thoracic blood shift and voluntary volume manoeuvres. Elite freedivers achieve deeper limits through training and glossopharyngeal technique than static body plethysmography alone would predict [13].

Diffusion capacity (DLCO/TLCO)

The diffusion capacity for carbon monoxide (DLCO) measures gas transfer across the alveolar-capillary membrane. A marked increase in diffusion capacity has been described during immersion and under increased hydrostatic pressure, which is attributed to increased pulmonary blood filling. In contrast, a postdive decrease may be interpreted as an indication of incipient interstitial pulmonary oedema [16]. Changes in diffusion function and mid-expiratory flow rates have also been reported following simulated saturation dives at great depths [16]. The diffusion capacity is therefore more suitable as a monitoring and safety parameter for detecting dive-induced pulmonary stress than for the prospective prediction of individual depth capacity.

Results

Comparative evaluation of the methods

Table 1 summarises the methods discussed in terms of their direct relevance to maximum diving depth, their practicality in everyday sports medicine practice, and their key limitations.

Table 1: Comparison of pulmonary function diagnostic methods for assessing apnoea diving depth

Method	Parameter measured	Relation to maximum diving depth	Practicality	Key limitation
Spirometry (VC, FVC, FEV1, FEV1/FVC)	Dynamic and static expiratory volumes	Indirect marker of oxygen storage capacity; correlates with apnoea time, not directly with depth	Very high (suitable for field use)	Does not measure residual volume or thoracic compliance
Body plethysmography (TLC, RV, RV/TLC ratio)	Static lung volumes including residual volume	The RV/TLC ratio is used to calculate the theoretical depth of thoracic compression ('squeeze' limit)	Moderate (laboratory-based, requires a chamber)	Static snapshot; does not capture dynamic blood displacement
Chest /lung compliance measurement (oesophageal balloon)	Transpulmonary pressure, elastic compliance	Higher compliance allows for greater volume reduction without tissue damage during deep compression	Low (invasive, research settings only)	Hardly available clinically; data limited to a few elite divers
Diffusion capacity (DLCO/TLCO)	Gas transfer across the alveolar-capillary membrane	Acute increase in DLCO during immersion as an indication of pulmonary capillary filling; post-dive decline as a sign of oedema	Medium (laboratory procedures)	Little longitudinal data on depth correlation
Glossopharyngeal insufflation/exsufflation (GI/GE) as a functional test	Maximum achievable lung volume above TLC or residual volume below RV	Direct extension of the calculated depth limit; highly technique-dependent	Low to medium (requires training, safety risk)	Increased risk of barotrauma and haemodynamic complications; not standardised
Lung sonography (B-line score)	Extravascular pulmonary fluid / subclinical oedema	An increase in B-lines correlates with dive depth and post-dive hypoxaemia; retrospective stress marker	High (suitable for field use, non-invasive)	Assesses sequelae, not prospective depth capacity
Chest CT / MRI	Morphology, lung volumes, detection of oedema	Precise volumetry and detection of microhaemorrhages following extreme dives	Low (radiation exposure/costs, not suitable for field use)	Not a prospective screening parameter; primarily descriptive

Measurement Results

Table 2 presents the descriptive data for the two participant groups. The average dive depth for both AIDA freediving and SCUBA diving is given. The data on average dive depth,

the AIDA freediving time STAT (static freediving) and The freediving distance (DYN) was derived from the competition results and a clinical-static freediving test (STAT-SCUBA) carried out during the examinations.

Table 2: Descriptive data of the participants

	AIDA (n=30)		SCUBA (n=30)	
	Mean	SD	Mean	SD
Age (years)	47.9	11.9	50.0	12.0
Gender (1=m; 2=f)	1.3	0.5	1.3	0.5
Height (cm)	177.4	7.7	175.8	8.4
Weight (kg)	74.4	15.0	81.8	15.7
Diving depth (m)	40.9*	17.2	22.6	18.4
STAT (min)	05:03:51*	01:02:17	02:47:09	01:26:21
DYN (m)	110.0	31.9	0.0	0.0

*p<0.05 t-test

In the studies, we used spirometry as the standard method for assessing diving medical fitness; the results are shown in Table 3. Significant differences were found between the AIDA and SCUBA groups in forced vital capacity (FVC). The

forced vital capacity differed by 700 ml between AIDA and SCUBA. There were no significant differences in any of the other standard parameters of the spirometric tests.

Table 3: Spirometry

	AIDA		SCUBA	
	Mean	SD	Mean	SD
VCmax (l)	5.40	1.24	4.80	1.19
FVC (l)	5.26*	1.26	4.56	1.16
FEV1 (l)	3.81	0.91	3.45	0.77
FEV1%VCmax (%)	70.68	6.49	72.71	8.70
PEF (l/s)	7.36	2.32	7.24	2.07

*p<0.05 t-test

Table 4 presents the results of the body plethysmography examinations for the two diving groups. Significant differences were observed in the results for total lung capacity (TLC),

functional residual capacity (FRC) and the sum of functional residual capacity and residual volume (RV).

Table 4: Body plethysmography

	AIDA		SCUBA	
	Mean	SD	Mean	SD
TLC (l)	7.46*	1.32	6.68	1.30
FRC (l)	3.93*	0.86	3.38	1.04
RV (l)	2.34	0.68	1.96	0.70
FRC+RV (l)	6.27*	1.40	5.35	1.64
VCmax (l)	5.12	1.13	4.73	1.07
FVC (l)	4.98	1.13	4.61	1.08
FEV1 (l)	3.82	0.92	3.63	0.82
FEV1%VCmax (%)	74.35	5.81	77.23	5.94
PEF (l/s)	8.25	2.20	8.38	1.91

*p<0.05 t-test

Diffusion Capacity (DLCO)

The measurement of diffusion capacity (DLCO) is of central importance in the assessment of freedivers, as it goes beyond mere lung volume and quantifies the efficiency of gas exchange at the alveolar-capillary membrane. An increased DLCO is less attributable to an enlargement of the lungs themselves and more to an increase in the functional exchange surface area and the capillary blood volume in the alveoli. The Krogh transfer coefficient (KCO) is the DLCO per unit of ventilated volume and describes the efficiency of gas

exchange per alveolus in the ventilated regions; it did not differ significantly. The DLCO determines the absolute amount of carbon monoxide transported per unit of time and pressure difference across the entire lung surface. It differed significantly between AIDA and SCUBA divers. The difference was $850 \pm 770 \mu\text{mol}/\text{min}/\text{kPa}$. Furthermore, in the diffusion test, the functional residual capacity (FRC) also differed significantly between AIDA and SCUBA divers by $520 \pm 160 \text{ ml}$. Table 4 shows the parameters of the diffusion capacity measurement.

Table 5: Diffusion capacities

	AIDA		SCUBA	
	Mean	SD	Mean	SD
DLCO (mmol/(min·kPa))	8.93*	2.26	8.08	1.49
KCO (mmol/(min·kPa))	1.30	0.21	1.31	0.17
VA (l)	6.83	1.17	6.22	1.12
TLC (l)	6.99	1.19	6.40	1.10
FRC (l)	3.57*	0.94	3.05	0.78
RV (l)	2.19	0.14	1.95	0.48

*p<0.05 t-test (VA = alveolar ventilation)

Based on the various studies on lung capacities and diffusion capabilities, a calculation was carried out to predict the probability of the dive depth, using the average dive depth achieved, by comparing lung capacities and deriving different results from the individual studies. The probability of prediction ranged between 78 and 93 per cent.

In order to incorporate a physiological component into the calculation, as opposed to simply comparing lung capacity values (TLC), we compare the relationship to alveolar ventilation (VA), as alveolar ventilation describes

the proportion of the tidal volume that actually reaches the alveoli and actively participates in gas exchange. The probability of predicting the depth reached was 79 per cent.

In a further step, the lung capacity values were calculated using the respiratory dynamics factors (FEV1 and FEV1/VCmax) in relation to total lung capacity, as the FEV1 and FEV1/VCmax values allow indirect assessments of lung compliance and airway resistance, and enabled functional assessments with a predictive probability for diving depth of 94 per cent.

Table 6: Calculation of diving depth from lung examinations

	AIDA		Prediction probability
	Calculated Diving depth (m)	Achieved Diving depth (m)	
RV/TLC body plethysmography	31.6±8.2	40.9±17.0	77.3 %
RV/TLC diffusion	31.6±8.2	40.9±17.0	77.3 %
RV/FRC+RV body plethysmography	37.1±5.0	40.9±17.0	90.7 %
RV/FRC+RV diffusion	38.0±4.6	40.9±17.0	92.9 %
RV/VA diffusion	32.3±8.4	40.9±17.0	78.9 %
FEV1/TLC*FEV1/VCmax	38.3±8.5	40.9±17.0	93.6 %
FRC/DLCO diffusion	41.2±10.3	40.9±17.0	100.7 %

When the relationship between functional residual capacity (ventilation) and the diffusion of carbon monoxide in the pulmonary circulation (perfusion) was assessed for predictive accuracy, the results showed 100 per cent accuracy. The values are presented in Table 6.

Discussion and Clinical and Sports Medicine Implications

For sports medicine practice, the literature does not identify a single, validated screening method for individual deep-diving prognosis in freedivers.

The difference between AIDA and SCUBA divers observed in spirometry lay in the forced vital capacity (FVC) of 700 ml, which described the ability of AIDA divers to dynamise air in the airways with maximum force and speed, suggesting better lung compliance and lower lung resistance.

In body plethysmography, the differences between AIDA and SCUBA divers were evident in a higher total lung capacity (TLC +780 ml), an increased functional residual capacity (FRC +550 ml) and, indirectly, an increased residual volume (FRC+RV +1172 ml) in favour of the freedivers, which initially suggested improved diaphragmatic mobility and freediving training.

In the diffusion tests, there was a difference in diffusion capacity of +850 mmol/(min*kPa) and an increase in functional residual capacity of 520 ml in favour of the AIDA divers, which could indicate the physiological capacity for a favourable ventilation-perfusion ratio for deep diving.

It therefore seems sensible to use a stepwise diagnostic approach for predicting individual diving depths. A basic spirometric examination to verify bronchopulmonary respiratory dynamics (FEV₁ and FEV₁/VCmax), supplemented by body plethysmography to determine RV, FRC and TLC, followed by a diffusion test for CO (DLCO), could therefore be used to estimate the theoretical mechanical depth limit. Physiologically, the ratio of functional residual capacity (FRC) to diffusion capacity (DLCO) most accurately reflected the ventilation-perfusion ratio in the thorax and best represented the diving depth achieved.

Using spirometry and body plethysmography, the following formula was derived:

FEV1/TLC * FEV1/VCmax (unitless)

the possible diving depth could be predicted with a 93.6 per cent probability. From the diffusion test, the following formula:

FRC / DLCO in l/min/kPa

the achievable diving depth could be predicted with 100 per cent probability.

Limitations of the Current Evidence

The available studies are predominantly based on small samples of elite divers (often n < 20), which limits their statistical validity and generalisability. Most studies are cross-sectional studies or case series; controlled, prospective studies with standardised depth measurement are largely lacking.

Calculated depth limits (e.g. from RV/TLC) are partly based on individual case calculations and model assumptions, rather than on systematically validated predictive models.

Ethical and safety constraints limit experimental investigations in extreme conditions, meaning that much of the knowledge stems from voluntary observations of competitive athletes.

The applicability to recreational or novice divers is limited, as fitness levels and technical proficiency significantly alter the measured correlations.

Conclusion

To date, no single pulmonary function test has been able to reliably predict the maximum apnoeic diving depth. Basic spirometric parameters, in the context of the relationship between FEV1 and TLC, correlated with the ratio of FEV1 to VCmax, yielding a predictive probability of 93.6 per cent. The RV/TLC ratio derived from body plethysmography provided an indicative, mechanistically based relationship to the theoretical depth limit; however, it is significantly influenced by physiological factors, which was reflected in a predictive probability ranging from 77.3 to 92.9 per cent, depending on the test used.

Using diffusion capacity testing and the associated thoracic ventilation-perfusion ratios, it was possible to predict the average diving depth achieved by 30 AIDA freedivers with an accuracy of almost 100 per cent.

Future, larger-scale prospective studies with standardised depth protocols are required to develop combined, clinically applicable predictive models.

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