Pulmonary Barotrauma in Divers During Emergency Free Ascent Training: Review of 124 Cases

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Introduction: Experience from treating diving accidents indicates that a large proportion of divers suffering from pulmonary barotraumas (PBT) or arterial gas embolism (AGE) were engaged in training dives, specifically emergency free ascent (EFA). We tried to verify this relationship and to calculate, if possible, the risk associated with normal recreational dives, training dives, and EFA training dives. ***Methods:*** All diving accidents treated at the Centre for Hyperbaric Oxygen Therapy (Brussels, Belgium) from January 1995 until October 2005 were reviewed. Data on the average number of dives performed and the proportion of in-water skills training dives were obtained from the major Belgian dive associations. ***Results:*** A total of 124 divers were treated, of whom 34 (27.4%) were diagnosed with PBT. Of those, 20 divers (58.8%) had symptoms of AGE. In 16 of those, EFA training exercise was deemed responsible for the injury. The association between EFA training and PBT proved to be very significant, with an odds ratio of 11.33 (95% confidence interval: 2.186 to 58.758). It was possible to calculate that a training dive (0.456 to 1.36/10,000) carries a 100 to 400 times higher risk, and an ascent training dive (1.82 to 5.46/10,000 dives) a 500 to 1500 times higher risk for PBT than a non-training dive (0.0041 to 0.0043/10,000 dives). ***Discussion:*** This study confirms a significant association between EFA training dives and the occurrence of PBT.

Keywords: diving, scuba, arterial gas embolism, training safety.

THE INTERNATIONAL diving market is no longer dominated by experienced and intrepid divers. Given that a full basic course can be completed within 3 to 5 d and that diving has become more affordable, there are more and more non-athletic people taking up the sport. This accounts for the massive increase in numbers of divers during the last two decades. For instance, a multinational federation such as the Professional Association of Diving Instructors (PADI) has issued 15,600,000 diver certifications globally. Their number of diver certifications has grown from 100,000 a year in the early eighties to more than 900,000 in 2008.

In this ever-growing market, safety of training is a critical issue. It was suggested in a previous recent study that one out of six diving injuries was caused by in-water skills training and one out of seven diving injuries was caused by emergency ascent training (9). Because of the inherent severe risks incurred by emergency ascent training, the necessity to practice such skills has been a controversial subject for more than three decades (10,13).

Back in 1977, during a UHMS workshop, it was concluded that training in such a skill should be maintained, but the training agencies (PADI, NAUI, SSI, YMCA) committed themselves to improving education techniques to lower the risks associated with the training procedures, and to give preference to the safest ascent procedure (16). Propositions from this workshop included abandoning rapid ascent training while exhaling without regulator, e.g., emergency free ascent (EFA), and limiting the depth of rapid ascent training to the 7-15 msw (20-40 fsw) zone. Despite these propositions, some diving certification agencies in Belgium still require many ascent skills, especially EFA, performed from a depth of 10 msw, 30 msw, and 40 msw. This skill is actually taught in Belgium without a regulator inserted in the mouth in an approach meant to mimic as closely as possible an emergency "out of air" situation. In addition to out-of-air and low-on-air situations, which are responsible for an average of 10% of diving incidents (1,4) and accidents (3,18), other specific activities that carry a great risk of pulmonary barotrauma (PBT) and arterial gas embolism (AGE) include out-of-air emergency ascent training and buddy-breathing ascent training (15). Both PBT and AGE occur more frequently in novice or inexperienced divers (7).

In order to draw lessons from in-field experience, as recommended by the European College of Hyperbaric Medicine (2), and to evaluate the methodology of diving instruction in Belgium, the aim of this study was to clarify the relationship between PBT, the most serious diving accident, and in-water skills during dive training. This will allow us to add a medical viewpoint in this debate that might lead to altering training procedures in order to reduce exposure to the high-risk task while maintaining or enhancing adequate knowledge of how to manage such situations.

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METHODS

Case Selection

This study was not supported by any grant; none of the researchers has a conflict of interest to declare. We reviewed all the dive accident treatment records from January 1995 until October 2005 and analyzed all 124 cases of diving accidents treated at the Centre for Hyperbaric Oxygen Therapy. For all the divers, we recorded several data such as age, gender, diving certification, number of dives performed, years of experience, previous history of dive accident, type of accident, and circumstances of the accident. We extracted those files with a diagnosis of PBT with or without AGE.

Diagnosis of PBT was made if the following symptoms were present within 5 min of surfacing or in the presence of precipitating factors such as inadequate exhalation caused by panic, faulty apparatus, or water inhalation: cough, haemoptysis, substernal chest pain, pink frothy sputum, dyspnea with or without the presence of a pneumothorax, hoarseness, and subcutaneous emphysema. Diagnosis of AGE was made if the clinical manifestations also included one of the following symptoms: loss of consciousness, or neurological abnormalities such as confusion, aphasia, visual disturbances, paresthesia, vertigo, convulsions, etc. After the patient had recovered and could understand the request, each patient at the Centre for Hyperbaric Oxygen Therapy was informed and gave verbal consent for use of their case in studies where only group data are reported. In this study, when a case was identified for inclusion, the clinical information was loaded into a database that was stripped of individual identifiers.

Incidence Calculations

Even if some authors report that submarine escape ascents can be safely performed provided that subjects are medically screened and well trained (20), a review of submarine escape training injury data from 11 nations estimated that the incidence rate of PBT for buoyant ascent, where the trainee has his head in water and must breathe out continually during the ascent, is 1 to 19 per 1000 escapes (19). Under recreational scuba diving conditions these figures are likely to be underestimates. The accident rate in recreational divers is difficult to determine because the real total number of dives performed each year is not known. We, therefore, attempted to estimate the incidence of PBT during in-water skill training and during nontraining dives in our population of Belgian divers in the following way. Both language sections of the Belgian Underwater Federation, affiliated to the Confédération Mondiale des Activités Subaquatiques—World Underwater Federation, were contacted to request the number of affiliates, the number of certifications delivered from January 1995 until October 2005, and the average estimated number of dives per diver per year (**Table I**).

TABLE I. TESTING DATA FROM THE BELGIAN UNDERWATER FEDERATION, 1995–2005.

	Certificates Issued (*N*)	TD Required (*N*)	AS Required (*N*)	TD Total (*N*)	AS Total (*N*)
4-Star Divers	1408	7	3	9856	4224
3-Star Divers	4974	12	3	59,688	14,922
2-Star Divers	10,680	14	3	149,116	32,040
Total	17,062			218,660	51,186

The Belgian Underwater Federation had a mean of 19,470 members during the period 1995-2005.
TD: training dives, AS: ascent training dives.

Based on retrospective data obtained from their affiliated dive clubs, the Belgian Underwater Federation (BUF) estimates that on average, some 50 dives are performed per diver per year. From the data obtained from our patients, the accident victims performed a total of 38,347 dives over a cumulative period of 716 yr, yielding an average number of 53.55 dives per year, which is quite consistent with the estimated annual number of dives in the BUF divers. As the number of divers in the BUF appeared to be quite stable over these years, around 19,470 divers (19,253–19,693), we used their average number of 50 dives per year to estimate an average total number of dives per year in Belgium at 973,500 dives.

Another problem when trying to evaluate dive-training safety is to determine the proportion between training dives and nontraining dives. In the BUF, diving courses are designed the same way for all diver certifications: students must satisfactorily demonstrate theoretical knowledge skills and in-water skills (training dives, TD). The latter are performance requirements such as (according to the level of certification): 800, 1000, or 1500 m snorkel swim; 50, 100, or 150 m inert dive tow; 500, 1000, or 1500 m full scuba equipment swim; orientation skills (100 m straight line surface swim with compass); leadership skills, where students accept limited responsibility for certified divers within the context of leading or managing diving activities; and finally, diving ascent skills (AS).

Ascent skills are composed of:

- "Buddy breathing," where buddy divers are sharing a single air source in the stationary position before proceeding to the ascent swim;
- "Assisted ascent," where diver demonstrates the use of positive buoyancy as an ascent aid for surfacing an unresponsiveness diver; and
- "Emergency free ascent" (EFA), where the diver performs a controlled emergency swimming ascent without a regulator in the mouth and establishes positive buoyancy at the surface.

All these ascent exercises are performed from a depth ranging from 10 to 40 msw according to the level of certification. There is no formal training before attempting these ascents; customarily the students only receive an oral explanation of the exercise and try to meet the underwater requirements during the dive that follows. In case of failure they can try again another day. All other types of dives are considered nontraining dives.

That is why, in order to estimate the total number of TD, we multiplied the number of certifications delivered during our time interval by the number of exercises (skills test) for each certification. There are 7 exercises

for four-star divers, 12 for three-star divers, and 14 for two-star divers. Of those exercises, three are AS. During a TD, only one AS can be performed and evaluated. This is why test dives required and number of exercises (in-water skills) required to achieve a certain certification level are equivalent.

The Belgian Underwater Federation, 1995-2005, had a mean of 19,470 members. Assuming that each skills test is successful at the first attempt, the total number of TD would be 218,660 TD, of which 51,186 would be AS. In reality, these exercises often require more than one attempt. Therefore, to estimate the incidence we provide three alternative calculations, taking into account one, two, or three attempts on average for each exercise. The actual incidence would be expected to fall within the lower and the upper limit of the calculated incidences because the number of attempts per person would vary, depending on their individual success. Thus, based on this methodology, we obtain the following incidence calculation parameters:

- Total number of dives performed annually: 973,500;
- Total number of dives during observation period: 9,897,250;
- Total number of TD during observation period: between 218,660 (one attempt) and 655,980 (three attempts); and
- Total number of AS during observation period: between 51,186 (one attempt) and 153,558 (three attempts).

Results were analyzed with GraphPad Prism software (version 3.06) on the PC, using the Fisher's exact test and the Chi-square test.

RESULTS

From the 124 injured divers treated, 34 (27.4%) were diagnosed with PBT. Of those, 58.8% (20 divers) had symptoms of AGE. Almost all these divers suffered loss of consciousness; some of them were in extremely critical condition, with deep coma and quadriplegia. There were no fatalities.

Risk of Pulmonary Barotrauma During Diving Activity

From the 34 cases with PBT, 30 (88.2%) occurred during the performance of in-water skills training and 4 (11.8%) during normal (nontraining) dives. From the 30 cases during training dives, 28 occurred during the performance of ascent training (EFA or other ascent techniques). Thus, it seems that ascent training is responsible for the vast majority of PBT cases (28/34 cases, 82.3%).

From the estimates of the Belgian Underwater Federation, an average of 973,500 dives is performed each year in Belgium (total 9,897,250 dives during the observation period). The number of training dives would, according to our alternative calculations, be either 218,660 (one attempt), 437,320 (two attempts), or 655,980 (three attempts). Of those, the number of ascent training dives would then, respectively, be 51,186, 102,372, or 153,558. According to this, the incidence of PBT can be estimated between 0.0041 and 0.0043/10,000 nontraining dives, between 0.457 and 1.37/10,000 training dives, and between 1.82 and 5.46/10,000 ascent training dives (**Table II**).

TABLE II. INCIDENCE PER 10,000 DIVES CALCULATED USING ALTERNATIVE ASSUMPTIONS ABOUT WHEN DIVERS PASSED THEIR SKILLS TEST ON THEIR FIRST, SECOND, OR THIRD ATTEMPT.

		TD	AS	OT
	PBT (N)	30	28	4
First	Total dives (N)	218,660	51,186	9,678,594
Attempt	Incidence	1.37	5.46	0.0041
Second	Total dives (N)	437,320	102,372	9,459,934
Attempt	Incidence	0.68	2.73	0.0042
Third	Total dives (N)	655,980	153,558	9,241,274
Attempt	Incidence	0.457	1.82	0.0043

PBT: pulmonary barotrauma, TD: training dives, AS: ascent training dives, OT: all other types of dive.

A Chi-square calculation for a 2-sided *P*-value gives a value of $P < 0.0001$, considered extremely significant.

PBT and Type of Training Dives

Of the 30 cases of PBT having occurred during the performance of in-water skills training, 16 occurred during EFA training (53.3%). In the remainder of cases, other ascent training (buddy breathing, assisted ascent: 12 cases) or swimming pool training (rapid ascent caused by underwater panic: 2 cases) was involved. From the 124 injured divers in our database, 19 other accidents (non-PBT) occurred during in-water skills training. Of these, 17 were non-EFA related (including middle and internal ear barotrauma, decompression sickness), and two occurred during EFA training (underwater panic, not requiring any specific treatment).

The association between PBT and EFA proved to be very significant ($P = 0.002$, two-sided *P*-value, Fishers exact test; **Table III**). Using the approximation of Wolf, the Odds Ratio is 11.33 (95% confidence interval of 2.186 to 58.758). This means that we cannot consider this Odds Ratio equivalent to a relative risk, firstly because the study is a retrospective one, and secondly because the tolerance to confound both values is only accepted when the Odds Ratio is close to 1 (6,8).

DISCUSSION

PBT is one of the most serious diving accidents. It results from overexpansion of the lungs when the victim, after having breathed compressed gas at depth, does not or cannot properly exhale the expanding pulmonary gas volume during a fast reduction of ambient pressure

TABLE III. ASSOCIATION BETWEEN EMERGENCY FREE ASCENT (EFA) AND PULMONARY BAROTRAUMA (PBT) FOR IN-WATER TRAINING.

	PBT	Other Injury (No PBT)	Total
EFA	16	2	18
Other Training Dives (No EFA)	14	17	31
Total	30	19	49

$P = 0.002$, two-sided; odds ratio 11.33 (95% confidence interval of 2.186 to 58.758).

(such as an emergency ascent). AGE secondary to PBT is one of the leading causes of death in the recreational diving community (12). Based on data from the injured divers treated at our center during a 10-yr period, the risk of PBT is dramatically higher during training dives (100-400 times) and specifically during ascent training dives (500-1500 times) than during "normal" diving activity. Confronted with such a risk, the benefits of the EFA training procedure must be well weighted and balanced against the risk of being threatened with such an emergency situation. Indeed, since the creation of this exercise, improvements in dive gear reliability (buoyancy compensating jacket, air pressure gauge, etc.) and the evolution of diving practice (air pressure monitoring, "buddy diving" system, etc.) have limited the number of "out-of-air" situations requiring an EFA.

From the point of view of many diver federations, including the BUF, EFA exercises should, however, be maintained to train the diver to respond safely to such an "out-of-air" situation by exhaling during ascent to prevent PBT. A review of sports diving accident statistics suggests that breath holding during ascent is the commonest cause of PBT and AGE (14). However, it may be interesting to note that from international diving accident databases, "out-of air" and "low-on-air" situations are more responsible for DCS, and not so much for PBT (3,18). This is confirmed in our database, where 30 of the 34 cases of PBT occurred during training dives and only 4 during nontraining dives. Therefore, it clearly appears that the training of this skill is more dangerous than the actual risk situation for which it was conceived.

There are some inherent limitations to this study, mainly concerning the representativeness of the divers in our database for the Belgian divers' population, and the lack of definite data on the dive exposures. Although not the only sports divers' federation in Belgium, the BUF is by far the largest group, and 83.33% of the divers from our database are affiliated with the BUF. There are many similarities between our population of injured divers and the BUF divers' population. First, the average age of our population is similar to that of the BUF (37.5 ± 10 yr vs. 40 ± 11 yr). Secondly, the average number of dives performed per year is 53.55 dives, which is consistent with the estimates by the BUF of approximately 50 dives per diver per year. Finally, the proportions of dive certifications between the BUF and our database are very similar. There are some differences, as our database does not contain any divers with no certification and has a slight overrepresentation of four-star divers and instructors. This might be explained by the fact that novice divers only perform swimming pool training without ascent training. The "one-star" certification is concluded with five open-water dives in shallow waters with no exercises. When these divers suffer injury they might not seek treatment from a recompression facility, as the main injury is middle ear barotrauma (11).

Approximately one-third of all diving-related injuries occurring in Belgium are referred to our Centre for Hyperbaric Oxygen Therapy. Data from the other hyperbaric center capable of treating life-threatening diving injuries indicate that since 2000, 130 injured divers were treated outside of our center, of which 11 were diagnosed with PBT (of which 1 died). Incidentally, five of these PBT were related to in-water dive training (9). As we had no access to the medical file and type of exercise performed, we did not include these cases in our database. From these figures, we can estimate that approximately 75% of all PBT injuries during this period were treated at our center, adding to the representativeness of our population.

The incidence calculation of any condition in recreational divers is difficult to determine because the total number of dives performed each year is not known, and must be estimated (17). When trying to evaluate dive training safety, an additional difficulty resides in determining the proportion between the total number of training dives and exploration or leisure dives. This also must be estimated. Despite these limitations, we have provided a range of incidence rates, reflecting either the "best-case" or "worst-case" scenario, and an intermediate.

Why would the EFA exercise, designed to teach divers the "correct behavior" while ascending, be so dangerous? A decrease of the pulmonary compliance has been suggested as a consequence of forceful attempts to exhale during rapid ascent. It has been hypothesized that vigorous attempts to exhale at low lung volumes—immersion has been demonstrated to result in airway closure and air trapping—predispose to PBT and AGE (5). This might be an explanation of our findings, as the protocol of the EFA exercise includes a rapid ascent without the regulator in the mouth, a forceful expiration, and the head tilted upwards (to "look to the surface").

According to this study, it is clear that EFA is a dangerous exercise. The cost-benefit ratio appears to be quite unfavorable. Maintaining the EFA exercise in its present form seems highly questionable. Modifications of the EFA exercise have been proposed in recreational scuba diving, such as a horizontal-movement emergency ascent training, which may provide a safer alternative while maintaining the goal of effective response teaching. Diver training in emergency ascent is important; it is, however, the responsibility of each diving federation or agency to develop the safest possible training program. Most Belgian sports divers' federations, including the BUF, have modified their ascent training protocols since 2006. It remains to be determined if the adopted modifications are less accident-prone. However, since then we have not had to treat any cases of PBT related to ascent training.

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