Decreased Incidence of Pulmonary Barotrauma After Discontinuation of Emergency Free Ascent Training

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INTRODUCTION: Because a significant association between training to perform emergency free ascent (EFA) and the occurrence of pulmonary barotrauma (PBT) was demonstrated in 2006, the Belgian Underwater Federation (BUF) decided to discontinue this procedure. An evaluation was needed 10 yr after the implementation of this change.

METHODS: All medical records with a diagnosis of PBT that occurred in Belgium from November 2006 to September 2016 were prospectively collected. Data on the proportion of in-water skills training dives were obtained from BUF.

RESULTS: A total of 5 cases of PBT were identified, significantly down from 34 cases in the previous 10-yr period. Of those cases, four occurred during training dives (two during ascent training). Analysis of the case files furthermore showed that two should have been medically disqualified from diving. Compared with the retrospective cohort (1995–2005), incidences are significantly reduced from 0.83 to 0.078/10,000 training dives and from 3.33 to 0.11/10,000 ascent-training dives; concomitantly, the incidence of PBT in nontraining dives also was reduced (from 0.0042 to 0.0014×10^{-4}/10,000 dives), possibly because less divers undertake the EFA procedure in case of a technical incident and have learned to solve the problem differently.

DISCUSSION: Discontinuation of emergency free ascent training was associated with a reduction in the incidence of PBT in the 10-yr follow-up period. We observed a significant decrease of PBT during training dives, confirming the hypothesis that EFA training in its previous form did not contribute significantly to diving safety.

KEYWORDS: diving, pulmonary barotrauma, arterial gas embolism, training safety.

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The Earth is surrounded by its own gravitational field, which exerts an attractive force on all objects; hence the old saying "what goes up, must come down." This needs to be modified in the case of scuba diving. A more accurate citation would be "what goes down, must come up"! Indeed, for every descent there must be an ascent. The preferred method is of course a normal, controlled, and planned ascent. Therefore, any unplanned event, where a diver aborts a dive due to equipment problems, out-of-air situation, an unpleasant encounter with marine life, or personal injury to the diver or another diver, and decides to ascend, may be defined as an "emergency ascent." It is a "last resort" response to an adverse event or perceived threat during a dive. Unfortunately, this type of procedure entails significant risks.

In an analysis of 947 recreational open-circuit scuba (self-contained underwater breathing apparatus) diving deaths from 1992–2003, emergency ascents were involved in 284 cases.[6] In 189 of these emergency ascents, a rapid ascent was witnessed or recorded. In 30 cases, divers attempted a free ascent without using a breathing gas supply. Low-on-gas/out-of-gas situations have been reported as the most frequent trigger of emergency ascents with fatal outcomes.[3,13] Since emergency ascent without breathing normally from a compressed gas source carries a risk of pulmonary expansion and thus pulmonary barotrauma ("burst lung"), scuba diving training agencies have committed themselves to promote safe ascent procedures while providing training in emergency ascent skills.[12]

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Problems arise when training for "how to handle an incident" would create a greater risk than that of an actual diving incident outside the training context. In 2009, based on a 10-yr retrospective series (January 1995–June 2005), our group showed that several diving practices were positively associated with mortality or morbidity, including skip-breathing (the deliberate use of long expiratory or inspiratory pauses in breathing), buddy-breathing (two divers sharing the same regulator mouthpiece, breathing in turns), and emergency free ascent (EFA) training. The association between training to perform EFA and pulmonary barotrauma (PBT) was very significant, with an odds ratio of 11.3 (95% confidence interval: 2.2 to 58.7) compared to normal training dives.[8] In the same study, it was also possible to estimate that the risk of PBT was dramatically higher during training dives (100–400 times) and specifically during ascent training dives (500–1500 times) than during "normal" diving activity. In the wake of this analysis, the Belgian Underwater Federation (BUF) decided in mid-2006 to significantly modify their protocols with the aim of avoiding the most dangerous diving practices or managing low-on-gas or out-of-gas situations.[9] While the two sections of the BUF (French and Dutch speaking) adopted slightly different modifications, both ceased the practice of ascent training without the mouthpiece in place. However, even if the scientific value of our conclusions was generally recognized, the decision was certainly in part motivated by fear of legal action should an accident occur during EFA training after this publication. Even up to today some express their doubts as to whether suppression of EFA training was really necessary and maybe would lead to more accidents in normal diving. Indeed, even though the risks of emergency ascent training were well identified, the benefits of omitting the training were not so immediately obvious. This is why an intense debate still persists between those who applaud the avoidance of exposure to the high-risk training exercises and those who would advocate reintroducing this kind of training in order to maintain or enhance adequate knowledge of how to manage such situations.

We therefore decided to perform a follow-up analysis to evaluate the risk-benefit ration of EFA training discontinuation on the occurrence of PBT. Indeed, an increase of PBT would likely unmask any discrete or nonobvious benefit from EFA training.

METHODS

From November 2006 on, we prospectively recorded the incidence of PBT in our hyperbaric center and specifically noted its association with training or nontraining dives. During and after a 10-yr period, we completed this with a detailed search for PBT cases from other sources. In Belgium, there are 10 hospital-based hyperbaric centers; however, only four of them have the personnel and expertise to treat injured divers. Although dispersion among multiple treatment sites does not facilitate data gathering on diving accidents, crossing information obtained from several sources [hyperbaric centers, Divers Alert Network (DAN) Europe Emergency Hotline, insurance, Belgian Underwater Federation, press or web forums] allowed us to be reasonably certain that the majority, if not all diving accidents, which have occurred in Belgium from November 2006 to September 2016, were collected. Patients with a diagnosis of PBT were prospectively recorded and their relevant data [i.e., age, dive experience (number of dive/year of diving), certification level…] was stored for further analysis. As in our previous study on the same subject,[8] 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 likely inadequate exhalation during rapid ascent (caused by panic, faulty apparatus, out-of-gas situation, or water inhalation): cough, hemoptysis, chest pain, pink frothy sputum, dyspnea with or without the presence of a pneumothorax, hoarseness, and subcutaneous emphysema. Furthermore, cerebral arterial gas embolism (CAGE) from PBT was diagnosed if loss of consciousness or clear neurological abnormalities such as confusion, aphasia, visual disturbances, paresthesia, vertigo, or convulsions were also present.

As each patient was informed and gave verbal consent at the time of treatment that their anonymized data could be used in future analyses of a mainly epidemiological nature, national and institutional requirements did not require ethical review and approval (Academic Committee of Bioethics, Brussels) as long as the data were stored in a database stripped of any individual identifiers. Nonetheless, this study was conducted in accordance with the Declaration of Helsinki.[14]

The incidence rate of diving accidents in recreational divers is difficult to determine in epidemiological studies because, even though the numerator may seem obvious (number of accidents per year), the denominator, i.e., the real total number of dives performed each year, can only be estimated. Therefore, we attempted to produce an estimated incidence of PBT during in-water skill training and during nontraining dives as previously described.[8] In short, the number of certifications delivered to divers from the Belgian Underwater Federation was obtained. The BUF is the only diving federation in Belgium keeping a detailed record of each of their members' training activity and certification status. Then, based on the number and nature of training exercises for each certification level, the number of training dives (TD) and ascent training dives (ATD) was estimated. As most of these exercises require more than one attempt before being successfully executed, we made, as in our previous study, three alternative calculations, from the best-case scenario (success at first attempt in all exercises) to the worst-case scenario (success only after three attempts of each exercise).

The total number of dives performed per year was obtained by multiplying the number of BUF members with the average number of dives performed by each diver, as reported in a recent survey.[7] Statistical analysis of the occurrence was performed using Graphpad Prism (version 5.0f for Mac, GraphPad Software, San Diego, CA) using the Chi-squared test.

RESULTS

A new incidence rate calculation was needed, as several changes were observed compared to our previous study that affected the exposure. Firstly, our reference population seems to have significantly decreased compared to the previously studied period (1995–2005). Over the last 10 yr, BUF witnessed a significant membership decrease, from an annual average of 19,470 to 15,124 divers (yearly numbers ranging from 13,722–16,626 divers, SD 1055). This population, albeit reduced, seems to have remained quite stable over the 2006–2016 period. Based on data from a recent survey,[7] we have used an average number of 51 dives per year per diver to estimate the average total number of dives per year in Belgium at 771,324 dives (down from 973,500 dives in our previous study).

Secondly, the certification level distribution of divers has changed: while each certificate level in the period 2006–2016 represents about one-fifth of the total, in 1995–2005 there was a much higher proportion of 3-star divers (ISO 24,801-3 "Dive Leader") (33% of the total) and the smallest groups were 4-star divers and Instructors (ISO 24,802-1 & 2 "Dive Instructor level 1 & level 2"; combined 18.5% of the total).

Finally, training courses were profoundly modified owing to the appearance of new certificate levels, the reduction of the necessary number of training dives to obtain a higher certification, and a complete overhaul of ascent skills exercises. Indeed, from 2009 onwards, the 4-star diver certificate was no longer issued, except as an honorary certificate, and was replaced by the Assistant Instructor certificate (ISO 24,802-1 "Dive instructor level"). Diving courses are still designed the same way for all diver certifications: students must satisfactorily demonstrate theoretical knowledge abilities and in-water skills (as evaluated by the instructor during training dives). For a more complete description of the general outlines of BUF diver training, see Lafère et al.[8] The main differences in ascent skills training (practiced during ascent training dives) were the discontinuation of EFA exercises, which were replaced by a more realistic rescue exercise (an "assisted ascent" followed by an inert diver tow at the surface), and the modification of the buddy-breathing protocol. The "assisted ascent" exercise (using positive buoyancy such as inflating the buoyancy control device) was maintained and not modified. Buddy-breathing is now only practiced in the stationary position, while during the ascent both divers (simulated victim and candidate) are breathing on their own dedicated regulator (the "octopus"). A recommendation not to practice ascent skills exercises when the water temperature is below 10°C has also been added.

By simple multiplication of the numbers of certifications delivered during the 2006–2016 period with the number of exercises (TD and ATD) required to be successfully executed in order to obtain such certification, we estimate the total number of dives performed by BUF divers during the observation period at 7,713,240 dives. In the same way, the total number of TD during the observation period can be estimated at between 312,311 (one attempt) and 936,933 (three attempts); and the total number of ATD during the observation period at between 111,063 (one attempt) and 333,189 (three attempts) (**Table I**).

During the studied period, no diving-related death was recorded among Belgian divers within the frontiers of the national territory and bordering area used by those divers. Nonetheless, five cases were diagnosed with PBT over this 10-yr span, down from 34 cases during the 1995–2005 period.

Of the patients, four were BUF members. Of those five cases, one occurred during a nontraining dive. The remaining four occurred during the performance of in-water skills training, of which two were ascent training dives and one was a swimming pool training. A brief description of cases is given below.

Case 1

A 54-yr-old man was a very experienced diver with more than 1200 logged dives over 10 yr. During the dive, he used a smaller compressed air tank than usual (7.5 L instead of 12 L), and later admitted to skip-breathing in order to save air. While on the bottom, he felt a stabbing pain in the chest and, upon surfacing, presented with cough and dyspnea. After 24 h, he was asymptomatic. After 48 h, he did a second dive. At the bottom, he experienced the same stabbing pain symptom in the chest and this time it was associated with severe dyspnea that necessitated an emergency ascent to the surface. He was evacuated to the nearest hospital and was diagnosed with a tension pneumothorax; there were no neurological symptoms. He was treated with chest drainage and subsequent chemical pleurodesis. A

Table I. Training Data from the Belgian Underwater Federation from 1995–2005 and 2006–2016.

	1995–2005					2006–2016				
	CERTIFICATES ISSUED *(N)*	TD REQUIRED *(N)*	ATD REQUIRED *(N)*	TD TOTAL *(N)*	ATD TOTAL *(N)*	CERTIFICATES ISSUED *(N)*	TD REQUIRED *(N)*	ATD REQUIRED *(N)*	TD TOTAL *(N)*	ATD TOTAL *(N)*
Assistant Instructor			N.A.			6456	4	3	25,824	19,368
4-Star Diver	1408	7	3	9856	4224	1589	7	3	11,123	4767
3-Star Diver	4974	12	3	59,688	14,922	14,396	9	3	129,564	43,188
2-Star Diver	10,680	14	3	149,116	32,040	14,580	10	3	145,800	43,740
Total	17,062			218,660	51,186	41,341			312,311	111,063

The Belgian Underwater Federation had a mean of 19,470 members during the 1995–2005 period and 15,124 members during the 2006–2016 period. TD: Training Dives; ATD: Ascent Training Dives; N.A.: not available.

2-star diver: ISO 24,801-2 "Autonomous Diver"; 3-Star diver: ISO 24,801-3 "Dive Leader"; 4-Star diver & Assistant Instructor: ISO 24,802-1 "Dive Instructor Level 1".

thoracic CT-scan revealed the presence of one pulmonary bulla (>3 cm in diameter) in direct contact with the pleura.

Case 2

An inexperienced 12-yr-old girl performed her fourth ever open water dive to obtain a Junior Open Water diver certification. The dive was in an in-shore lake, to a maximum depth of 10 m, and the total dive time was 37 min. Near the end of the dive, as her instructor asked her to do a mask removal and replacement, she lost control of her buoyancy and made a direct rapid ascent ("blow-up") from 5 m to the surface. Immediately, she presented with substernal chest pain, followed by transient loss of consciousness, confusion, and vertigo. Neurological symptoms were still present upon arrival at the hyperbaric center. After hyperbaric treatment, there was a full recovery without neurological or pulmonary sequelae.

Case 3

The victim was a 33-yr-old, moderately experienced diver (more than 100 logged dives) who was training to obtain his 3-star diver certification. During the assisted ascent exercise (ascending from 30 m of depth to the surface), he lost consciousness while ascending and was brought to the surface by his dive instructor. Although CPR was not necessary (the diver was unresponsive but spontaneously breathing), the victim was intubated (rapid sequence induction) by the assisting Emergency Medical Services team because of a Glasgow Coma Scale of 3 points, and immediately evacuated to the hyperbaric center. Although time to recompression was less than 2 h, the victim completed hyperbaric treatment with severe disabling memory and concentration disturbance and with speech difficulties. A brain MRI performed 1 mo after the accident was normal. It was discovered that the diver was an asthmatic on bronchodilator treatment, with a highly positive methacholine challenge test (>30% decrease in peak flow following trigger exposure). Moreover, a thoracic HRCT-scan revealed the presence of three pulmonary bullae (each >1 cm in diameter) in direct contact with pulmonary vessels.

Case 4

A 27-yr-old woman suffered a panic attack during an exercise, ascending from 30 m of depth to the surface while buddy-breathing, caused by water entering the mouthpiece during the exchange. She made a rapid uncontrolled ascent to the surface. Her diving instructor managed to grab her, emptied his own buoyancy control device and thus was able to somewhat reduce their ascent speed. Upon surfacing, she presented with cough, chest pain, pink frothy sputum, and confusion, without loss of consciousness. Upon on arrival at the hyperbaric center there was a positive Romberg test, inability to stand on one foot, and postural imbalance. After hyperbaric oxygen therapy, there were no sequelae.

Case 5

A 17-yr-old novice diver breathed directly on a tank valve (air escaping at a pressure of 180 bar) as instructed (unusual training exercise decided by the dive instructor and absolutely not recommended or proposed by BUF). The accident happened in a swimming pool at 3 m of depth; the training exercise involved repeated swimming between two tanks, opening the tank for a breath of air, and closing it again before returning to the other tank while breath-holding. Confused and panicking, he made a blow-up ascent from the pool bottom to the surface with his lungs full of air, and suffered immediate headache, progressive confusion, hemiparesis, and hemianopia. After hyperbaric treatment, a partial recovery was obtained (persistence of quadrant anopia, which further recovered completely over the following months). There were no pulmonary symptoms and he had a normal lung HRCT.

The incidence of PBT (number of PBT divided by the estimated TD or ATD calculated according to our different hypotheses of one to three attempts) in the period 2006–2016 is thus estimated between 0.042 and 0.128/10,000 training dives, between 0.06 and 0.18/10,000 ascent training dives, and between 0.0013×10^{-4} and 0.0015×10^{-4}/10,000 nontraining dives (**Table II**). The incidence differences between types of dives are highly significant (Chi-squared $P < 0.0001$, df 2).

Compared with the 1995–2005 period, the averaged incidence (mean of the 3-calculation hypotheses) of PBT seems to be reduced by a factor of 10 for TD (from 0.83 to 0.078/10,000 dives); by a factor of 30 for ATD (from 3.33 to 0.11/10,000 dives), and by a factor of 30,000 for nontraining dives (from 0.0042 to 0.0014×10^{-4}/10,000 dives). This reduction is highly significant (Chi-squared $P < 0.0001$, df 2).

DISCUSSION

Pulmonary barotrauma from diving is a rare event, but the consequences can be dramatic. Using a similar methodology and roughly the same diving population, we have shown that the suppression of EFA training by the Belgian Underwater Federation seems to have significantly reduced the number of PBT cases in Belgian divers. Regardless of the inevitable methodological difficulties, we can safely conclude that this change in

Table II. Incidence of PBT per 10,000 Dives Calculated Using Alternative Assumptions About Whether Divers Passed Their Skills Test on Their First, Second, or Third Attempt.

	TD	ATD	OT
PBT (*N*)	4	2	1
First Attempt			
Total dives (*N*)	312,311	111,063	7,400,929
Incidence	0.128	0.18	0.0013×10^{-4}
Second Attempt			
Total dives (*N*)	624,622	222,126	7,088,618
Incidence	0.064	0.09	0.0014×10^{-4}
Third Attempt			
Total dives (*N*)	936,933	333,189	6,776,307
Incidence	0.042	0.06	0.0015×10^{-4}

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

diver training has not resulted in a dramatic increase of PBT, a concern that was repeatedly voiced.

In fact, when examining the cases, it is obvious that Cases 1 and 3 were medically unfit to dive because of pulmonary conditions (possible pneumothorax from PBT days earlier, pulmonary bulla, symptomatic asthma)[4,5] and that Case 5 was an unfortunate swimming pool incident[1] possibly related to inadequate supervision. Case 4 happened during an EFA exercise similar to the EFA training that BUF had abandoned in 2006, illustrating again the hazards associated with those exercises. This leaves only Case 2, which could have, theoretically, been prevented by formal EFA training. However, this case concerns a 12-yr-old novice diver, who certainly would not yet have been scheduled to receive such training even in the "old" days. Furthermore, inadequate supervision may have played a role here.[11] Cases 1 and 3 had been trained according to the "old" training schedule, and had received EFA training previously, yet suffered PBT. This suggests that being trained in EFA does not constitute a bulletproof guarantee against PBT. Indeed, it has been demonstrated that neither instructors or candidates can properly evaluate lung volume reduction based on exhalation only.[10]

Training dives and especially ascent training dives still carry a much higher risk than nontraining, recreational dives. This is not surprising, as "training" implies that the diver has not yet mastered the skills that he or she is training for. An incorrect execution of the training task may result in physical injury and, during training dives or ascent training dives, this task is deliberately executed, sometimes repeatedly. The results of this study show that both training dives and ascent training dives carry a much lower absolute risk compared to the previous 10-yr period.

It is also worthwhile noting that the risk for PBT during nontraining dives seems to have significantly decreased. There are a number of possible explanations for this.

Firstly, suppression of EFA training was not the only measure taken by the Belgian Underwater Federation in 2006. They also placed more emphasis on general safety awareness, buddy monitoring, avoidance of ascent skills training in cold water, and introduced new courses with a special focus on dive planning and gas consumption. Indeed, running out of gas is, unsurprisingly, often followed by a rapid ascent to the surface.[2] An analysis of Australian recreational diving incidents has shown that the combination of running out of air and rapid ascent had a much higher resultant morbidity (91%) than merely running out of air alone (9%).[2,3] Possibly divers now use EFA less often in such situations, as they have been taught that, by itself, it is also dangerous, and resort to alternative solutions to their problem: buddy assistance with octopus, followed by assisted ascent. Therefore, by also addressing proper gas planning and correct behavior in case of low-on-gas situations, the Belgian Underwater Federation may have achieved more safety than by simply dicontinuing the EFA training exercises.

Secondly, we note a significant reduction in numbers of divers comparing both time periods and a change in distribution of the certification levels. This may be due to divers having ceased their diving activity or changed membership from the Belgian Underwater Federation to another federation (e.g., PADI, SSI). The exact numbers of Belgian divers who are members of those other federations is not known, and neither is it possible to ascertain their exact level and method of training. In Belgium, many of the instructors of these other federations implement training exercises similar to those of the Belgian Underwater Federation. We therefore chose to limit our analysis to these divers. However, even if the absolute number of divers has decreased, it can be seen (Table I) that the number of certifications that were delivered has been significantly increased, from 17,062 to 41,341, as have the number of training dives and ascent training dives performed. Both this increase in training dives and the reduction of PBT incidents account for the dramatic decrease of PBT risk during diving training. Moreover, even if only novice divers are considered, the calculated incidence is still significantly reduced by a factor of 20 at 0.04/10,000 training dives ($P < 0.001$), with no recorded PBT incidents during nontraining dives.

Our calculations use a lower total number of dives than in the previous period: 7,713,240 dives as compared to 9,897,250 dives between 1995 and 2005. In our first study we used an average of 50 dives per diver per year, which was based on an estimate provide to us by the BUF. The average diving activity of the 43 cases of PBT in our first study was 53.55 dives per year. In this study, we here have chosen 51 dives per year, a number obtained from a recent survey among Belgian Underwater Federation divers. Owing to the very small number of PBT cases, we could not match their average dive experience to this number. Even if one could argue that not every single Belgian Underwater Federation diver performs 51 dives per year, one would be surprised to observe the numbers of divers emerging from Belgian in-shore lakes in winter just as in summer. Therefore, we think it is justified to use this as a basis for our calculation.

Finally, it is of course possible that we have missed a number of PBT accident reports, even though we have taken care to carefully interrogate and scrutinize the same sources we used in our previous study. As there is no mandatory registration of causal factors in the national hospital case registration system in Belgium, divers who presented without notifying their diving federation or insurance may have been missed. However, had they been serious or life-threatening, these cases would most probably have shown up in one of our sources.

Evaluation of diving safety is traditionally based on accident/incident case reviews in which apparent associations are tacitly assumed to be causes.[6] In the light of our results, the leap from association to causality is not unreasonable. Indeed, the package of chances taken as a whole (discontinuation of EFA training from scuba diving training protocols, addressing proper gas planning, and correct behavior in case of low-on-gas situations) seems to have had an immediate, obvious, and directly favorable result in decreasing the incidence of PBT. Although some other factors may have played a role, it is our opinion that EFA training should not be reintroduced in recreational diving training. We believe our follow-up study shows that, generally, diving is now safer.

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