

Flying after diving: should recommendations be reviewed? In-flight echocardiographic study in bubble-prone and bubble-resistant divers

Danilo Cialoni, Massimo Pieri, Costantino Balestra and Alessandro Marroni

Abstract

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Introduction: Inert gas accumulated after multiple recreational dives can generate tissue supersaturation and bubble formation when ambient pressure decreases. We hypothesized that this could happen even if divers respected the currently recommended 24 hour pre-flight surface interval (PFSI).

Methods: We performed transthoracic echocardiography (TTE) on a group of 56 healthy scuba divers (39 male, 17 female) as follows: first echo – during the outgoing flight, no recent dives; second echo – before boarding the return flight, after a multiday diving week in the tropics and a 24-hour PFSI; third echo – during the return flight at 30, 60 and 90 minutes after take-off. TTE was also done after every dive during the week's diving. Divers were divided into three groups according to their 'bubble-proneness': non-bubblers, occasional bubblers and consistent bubblers.

Results: During the diving, 23 subjects never developed bubbles, 17 only occasionally and 16 subjects produced bubbles every day and after every dive. Bubbles on the return flight were observed in eight of the 56 divers (all from the 'bubblers' group). Two subjects who had the highest bubble scores during the diving were advised not to make the last dive (increasing their PFSI to approximately 36 hours), and did not demonstrate bubbles on the return flight.

Conclusions: Even though a 24-hour PFSI is recommended on the basis of clinical trials showing a low risk of decompression sickness (DCS), the presence of venous gas bubbles in-flight in eight of 56 divers leads us to suspect that in real-life situations DCS risk after such a PFSI is not zero.

Key words

Echocardiography, Doppler, bubbles, altitude, flying (and diving), recreational diving, remote locations, travel

Introduction

The risk of decompression sickness (DCS) may increase when flying after diving.¹⁻³ The minimum safe pre-flight surface intervals (PFSI) between diving and exposure to altitude have been well studied;⁴⁻⁶ however, all the studies were not performed in real diving and flying conditions but in simulated hyperbaric and hypobaric chambers.⁷ It has been estimated that the incidence of DCS decreases as the PFSI increases and beyond 11 hours there appears to be no additional DCS risk after single no-stop dives and beyond 17 h after repetitive, no-stop dives.⁸ Current guidelines suggest a minimum PFSI of 12 h after a single, no-stop dive, 18 h after multiple dives per day or multiple days of diving, whilst intervals substantially longer than 18 h are suggested after dives requiring mandatory decompression stops.⁸⁻¹⁰

The steady increase in popularity of scuba diving has implied an increase in flights to and from tropical destinations and, as a consequence, the risk of DCS during the return flight may be increased. For this reason, we thought further research was due and well justified. Our recent work has shown that subjects who were particularly prone to develop post-dive bubbles (venous gas emboli, VGE) showed significant amounts of circulating bubbles in-flight after an intense recreational diving week, notwithstanding a 24-hour PFSI.¹¹ Although asymptomatic, these could be the reason for some hyperintense spots seen in the cerebrum of divers on MRI.¹² Our hypothesis was that inert gas could linger in

the tissues for longer than 24 hours after multiple, multi-day recreational diving and that the rapid decrease in cabin pressure with altitude, causing further tissue supersaturation, could trigger new bubble formation in some divers, even in those who respected the current recommendations to delay flying for 24 h. This could explain certain DCS occurring in flight despite a correct PFSI.

We performed Doppler-echocardiography during real commercial return flights on subjects whom we had studied during a previous week of diving to better understand any possible 'predisposition' to bubble formation in flight.

Methods

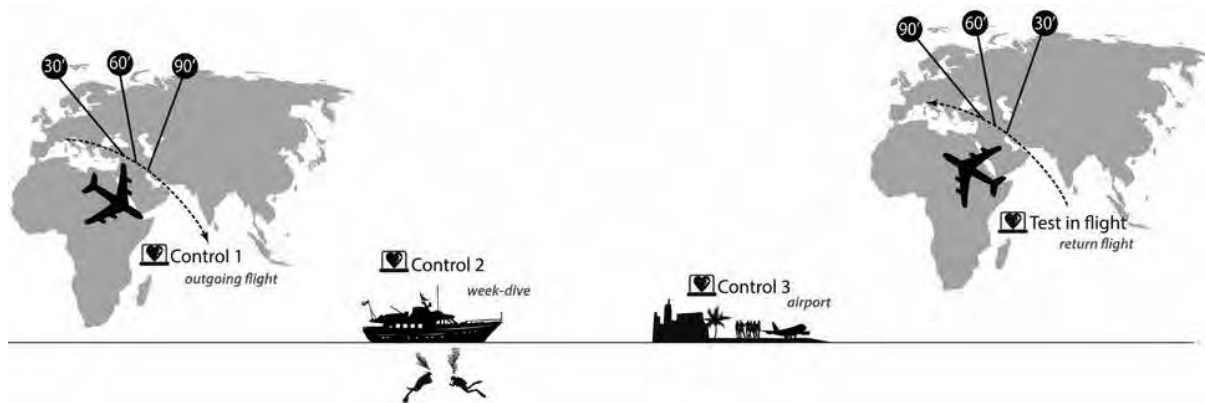
The study protocol was approved by the institutional ethics committee (Comite d'Ethique Hospitalier du CHU Brugmann, Brussels, Belgium; approval no: CE 2008/66). All participants were informed about the scope of the study, the procedures of the echocardiographic examination and gave their written informed consent.

SUBJECTS AND DIVES

We studied a group of 56 healthy, active, experienced divers. No subject had historical or clinical evidence of arterial hypertension, cardiac, pulmonary or any other significant disease. No subjects declared previous DCS. Information about age, gender and standard anthropometric data such as

Figure 1

Protocol description: Control 1 – trans-thoracic echocardiography (TTE) during the outgoing flight; Control 2 – TTE after every dive on every day of diving; Control 3 – TTE before boarding the return flight, after 24 hour pre-flight surface interval; test in flight – TTE during the return flight; TTE were performed at 30, 60 and 90 min after reaching cruising altitude



height and weight were recorded and the BMI calculated. Heart rate and arterial blood pressure were monitored, recorded daily and their means were calculated.

All divers concluded a full week of intensive recreational diving with 13 dives in total, two dives per day for five consecutive days plus one dive the day of arrival (check dive) one dive on the last day (24 hours before the return flight) and one night dive at mid-week. Two subjects did not make the last dive, therefore increasing their PFSI to approximately 36 hours. All divers made their planned dives without any restrictions or request imposed by the investigation protocol.

All divers did a safety stop of five minutes at 5 metres' sea water (msw) at the end of all dives. Dive computers (iDive pro, Dive system, Valpiana, Italy) provided by the Divers Alert Network (DAN-Europe) were used on every dive and all dive profiles were fully recorded.

Data about possible diving risk factors such as workload (light, moderate, heavy), current (absent or present) health problems (vertigo, seasickness, headache), problems during diving (difficulty in ear equalization, out of air, buoyancy, shared air, equipment problems) and alcohol use during the pre-dive 24 hours were collected by an ad-hoc questionnaire.

The gradient factor approach was used to measure the nitrogen supersaturation of the leading tissue at the end of each dive; this approach theoretically predicts the calculated maximum value allowed for all the 16 tissues included in the Buhlmann ZH-116 model C. All the gradient factor (GF) calculations were performed for each one of the 16 tissues and we reported the maximal GF value in the leading tissue. To estimate decompression stress we also calculated the Hennessy and Hempleman exposure factor (EF) ($p\sqrt{t}$; where p is the absolute pressure and t is the total time of diving).¹³

ECHOCARDIOGRAPHY

All the subjects were studied by trans-thoracic

echocardiography (TTE) after each dive during five diving trips and ten (five outgoing and five return) inter-continental Europe-Maldives flights on Boeing 767-300ER aircraft according to the protocol described below. TTE was performed by a commercially available instrument (MyLab 5, Esaote SPA, Florence, Italy) using a cardiac probe (2.5–3.5 MHz). All echocardiograms were recorded with the subjects lying motionless at rest on their left side breathing normally. Recordings were made for 20 sec and saved to the hard drive for subsequent analysis by two technicians with experience in transthoracic echocardiography. Analyses were performed frame by frame and, in cases of disagreement, the comparative analysis was repeated.

Bubbles were graded according to the Eftedal and Brubakk (EB) scale as follows:¹⁴

- 0 – no bubbles;
- 1 – occasional bubbles;
- 2 – at least one bubble per 4 heart cycles;
- 3 – at least one bubble per cycle;
- 4 – continuous bubbling;
- 5 – 'white out'; impossible to see individual bubbles.

After grading the divers, they were divided into three groups: non-bubblers (NB), occasional bubblers (OB) and bubblers (B). As well as those who never developed bubbles, subjects who only rarely showed solitary bubbles were included in the NB group. Subjects who usually showed only occasional low bubble grades were included in the OB group. Divers who consistently showed bubbles after every dive and only rarely showed low grade or no bubbles were included in the B group. We discriminated the three groups using a 'classic' EB grading scale. Differences in depth, diving time, GF and EF were analysed between the three groups (NB, OB and B).

STUDY PROTOCOL

The study used the following protocol (Figure 1):

- Control 1: during the outgoing flight to the Maldives, 30, 60 and 90 minutes after take-off;

- Control 2: during the diving week on every diving day; before diving and 30, 60 and 90 minutes after surfacing from each dive; if bubbles were detected, further scans were recorded;
- Control 3: before boarding the return flight, after a 24-hour interval from the last dive;
- In-flight test: during the return flight, 30, 60 and 90 minutes after take-off (mean ambient pressure 850.4 +/- 1.60 mbar, approximately 0.84 atm).

The subjects who were found positive to in-flight bubbles were also monitored after the 90-minute recording and every 30 minutes until complete echocardiograph battery exhaustion. Bubble grades were compared with the possible risk factors listed above.

ELECTRO-MAGNETIC INTERFERENCE PROTOCOL

Specific tests to evaluate electromagnetic interference (EMI) were agreed with the Airline (NEOS) to ensure that in-flight use of the echocardiograph would not generate any interference with the aircraft instrumentation. EMI were evaluated during a 'ground EMI test' as per avionic guidelines concerning the use of portable electronic devices on board aircrafts.¹⁷ Some of the alternating current equipment was tested operationally by means of a special testing set (NAV402AP equivalent) in order to reproduce simulated flight conditions, thus ensuring EMI would not arise at any time. During in-flight echocardiography, the correct operation of the navigation, communications, identification and safety instruments of the aircraft was tested according to the above-cited avionics protocol. All tests were performed with the echocardiograph in the tail section of the aircraft in the last three rows (NEOS Engineering Order 12-00-001: "B767 – Ground EMI Test for Medical Portable Electronic Device (PED) Mylab").¹⁵ Tests were also aimed at ensuring the correct operation of the echocardiograph during flight using an internal device within the Mylab 5 itself. Avionics engineers and the echocardiography technicians also checked for any macroscopically visible interference or malfunction of the respective devices. In accordance with the airline's request, in-flight avionic conditions and aircraft configurations were repeatedly replicated to rule out any possible interference. The echocardiograph was then classified according to avionic safety procedures as not being detrimental to native aircraft instrumentation.

CABIN PRESSURE MEASUREMENT

Cabin pressure was monitored every 15 minutes from take-off until four hours after reaching cruising altitude using a modified dive computer (iDive Pro, Dive System, Valpiana) and compared with the aircraft's native altimeter data over the same four-hour time period. The modified dive computer used a barometric sensor that measured in millibar (mbar) with adjustment to a Boeing 767 cabin pressure variation ratio of 500 feet (152.4 metres) per minute as a maximum and an error tolerance up to +/- 80 m. Differences across

the 10 flights (five outgoing and five return) were evaluated for stability of the peak cabin pressure to determine whether similar hypobaric exposure conditions occurred during the flights.

STATISTICAL ANALYSIS

Data are presented as the mean ± standard deviation (SD) for parametric data and median and range for non-parametric data (e.g., bubble grades). The median bubble grades of the three groups (NB, OB and B) were calculated and statistical differences were tested by non-parametric analysis of variance (Kruskal-Wallis test), after normality testing (Kolmogorov-Smirnov test). Differences between NB, OB and B for age, height, weight, BMI, heart rate, diastolic and systolic blood pressure were calculated by analysis of variance (one-way ANOVA for parametric data with Neuman Keuls post hoc test and Kruskal-Wallis for non-parametric data) and by chi-square test for gender, workload, current, health problems, problems during dives and alcohol use. Differences between NB, OB, B and dive profile (depth, time, ascent rates, safety stops, gradient factor, surface intervals) were calculated by analysis of variance (Kruskal-Wallis test). Differences in aircraft cabin pressure between the ten flights were assessed in the same way. A probability of less than 5% was assumed as a threshold to reject the null hypothesis. The recommendations of Hochberg and Benjamini for multiple comparisons were employed,¹⁶ and statistical significance levels were set at $P < 0.05$, $P < 0.01$ and $P < 0.001$.

Results

A group of 56 subjects (39 male, 17 female); mean age 46 +/- 12.2 years (48 +/- 12.5 for men and 43 +/- 11.1 for women) (mean +/- SD), mean height 174 +/- 8.7 cm (177 +/- 7.6 for men and 165 +/- 4.7 for women); mean weight 74 +/- 14.1 kg (79 +/- 12.6 for men and 62 +/- 9.2 for women); body mass index (BMI) 24 +/- 3.2 (25 +/- 2.8 for men and 23 +/- 3.4 for women) was studied. The mean depth of the 726 dives recorded was 30.2 +/- 7.7 msw while the mean time was 47.8 +/- 10.3 min. All divers respected 'normal' ascent rates (not slower than 9 msw·min⁻¹ and not faster than 18 msw·min⁻¹, as confirmed by the electronic dive logs) and completed the safety stop. No dive required mandatory decompression stops. None of the divers showed symptoms of DCS during the study.

TTE during the five outgoing flights to the Maldives and at the airport immediately before boarding the five return flights did not show any bubbles in the right or left sides of the heart in any diver. During the diving week, TTE showed that 23 of the 56 subjects never developed bubbles (NB group), 17 subjects only occasionally developed bubbles (OB group) and 16 subjects produced bubbles every day and after almost every dive (B group). The median and range of EB bubble grades of the three groups during the diving were: NB 0 (0–1); OB 0 (0–3); B 3 (0–5).

Table 1

Relationship between potential anthropometric, physiological and diving exposure risk factors and bubble-prone divers; means and (SD) or number of divers or % shown; there were no statistical differences between the three groups except for age; * $P = 0.04$ for non-bubblers vs. occasional bubblers; † $P < 0.001$ for non-bubblers vs. bubblers

Risk factor	Non-bubblers	Occasional bubblers	Bubblers
Anthropometric			
Height (cm)	174 (8.0)	171 (9.3)	175 (9.1)
Weight (kg)	73 (13.5)	72 (15.1)	76.5 (14.5)
BMI (kg·m ⁻²)	24 (2.9)	24 (3.3)	25 (3.6)
Males/females (<i>n</i>)	15/8	11/6	13/3
Age (yr)	41 (8.8)	45 (11.8) *	55 (12.5) †
Physiological			
Heart rate (beats·min ⁻¹)	76 (7.7)	74 (10.4)	75 (8.0)
Diastolic BP (mmHg)	77 (7.4)	75 (5.7)	74 (10.4)
Systolic BP (mmHg)	139 (24.0)	134 (11.5)	128 (12.6)
Diving factors			
Depth (msw)	30 (7.2)	31 (9.2)	31 (6.5)
Diving time (min)	47 (10.8)	47 (11.0)	49 (8.6)
Gradient factor (GF)	0.7 (0.2)	0.7 (0.2)	0.8 (0.1)
Exposure factor (EF)	27.2 (6.4)	28.0 (7.9)	28.4 (5.6)
Workload (% for each group from 726 reports)			
Light	39	29	37
Moderate	48	53	50
Heavy	13	18	13
Current (% for each group from 726 reports)			
Present	39	41	44
Absent	61	59	56
Diving problems (% for each group from 726 reports)			
No problem	87	82	87
Problem	13	18	13
Health problems during diving (% for each group from 726 reports)			
No problem	91	88	94
Problem	9	12	6
Alcohol (% daily use; 150 positive out of 390 reports)			
No	55	71	62
Yes	45	29	38

The differences in bubble grade between the three groups were statistically significant (all $P < 0.001$). There were no differences between the three groups for any of the anthropometric, physiological or diving parameters (Table 1) excepting that our previous observations were confirmed with respect to age, with an increase in age in the B group (55 +/- 12.5 years) compared to the NB (41 +/- 8.8 yr, $P < 0.001$) and OB groups (45 +/- 11.8 yr, $P = 0.04$).¹¹ We also did not find any difference in diving exposure factors (depth, diving time, GF and EF) between the three groups. There was no relationship between the B group and the additional risk factors investigated (workload, current health problems, problems during diving, use of alcohol; Table 1).

During the return flights, bubbles were detected in 8 of the 56 subjects, all from the B group (median bubble score 1, range 0–3; one subject with grade 3). Subjects classified as B during the diving week and who also showed in-flight bubbles had a statistically higher mean bubble grade after

every dive compared to those who, although B, did not develop in-flight bubbles ($P < 0.001$). Two subjects in the B group, with high bubble grades during the diving (median 3, range 2–4 and 2, range 0–3) did not make the last dive of the series, thus increasing their PFSI to approximately 36 hours. Because of this, both were excluded from the comparative analysis. Neither showed any bubbles on the return flight. In-flight bubble grades decreased as the flight progressed and by 90 min after take-off no bubble-positive subjects showed any bubbling and there was no evidence of a reverse trend (increasing bubble grade over time). An example of in-flight bubbles in the right heart is shown in Figure 2.

No malfunction of or interference with the aircraft's instruments were found during the ground EMI test. Similarly no EMI interference or malfunction of the aircraft's instruments or of the MyLab 5 echocardiography machine were observed during the flights. Aircraft cabin pressure

Figure 2

Case of in-flight high-grade bubbles; the arrows indicate bubbles in the right heart as recorded in-flight after a 24-h pre-flight surface interval; no bubbles could be seen in this subject pre-flight



showed no statistically significant differences between the 10 flights; mean pressure 850 +/- 1.6 mbar.

Discussion

The purpose of this study was to investigate if divers who, during a week's intensive recreational diving, had consistently shown VGE after every, or nearly every dive (B – bubblers) might respond to a new decrease in ambient pressure during flight with new circulating bubble formation, notwithstanding pre-flight computed non-critical inert gas tissue tensions and a 24-hour PFSI. To ensure that pre-flight diving was the only added variable and possible bubble trigger we had included TTE during the outgoing flight, without any diving for at least 72 hours pre-flight, and also before embarking on the return flight (after a 24-hour PFSI).

TTE performed after every dive on every diver during the diving allowed us to stratify the divers into three bubble groups (NB, OB and B). We discriminated the three groups using a 'classic' EB grading scale. This is consistent with our equipment, although we acknowledge that recent research indicates that, with newer echocardiography devices, it is common to observe EB Grade 4 bubbles in asymptomatic divers.¹⁷ Therefore, it would be more appropriate to use the 'expanded' EB grading scale with more modern devices to discriminate between the three groups more accurately.¹⁸

Statistical analysis across the three groups showed that the diving exposure for the divers was similar, even though we recognise that it is difficult to standardize real-world diving. This could be regarded as a limitation of the study. On the other hand, real conditions are not always perfectly

represented by simulated conditions.⁷ Our results show that, even if a 24-hour PFSI is respected, some subjects developed significant amounts of bubbles during the homeward flight, confirming our previous work.¹¹ The larger numbers of subjects investigated showed that only those subjects who consistently showed high bubble grades during the diving developed bubbles in-flight. Interestingly, the two highest bubble graders, who were advised to omit the last diving day, and boarded the plane about 36 hours after their last dive did not show any bubbles in-flight. This allows us to speculate that a longer PFSI is needed in divers with high bubble grades.

Lastly, the decrease in in-flight bubble grades as flight time elapses can be interpreted as indirect evidence that a certain level of possibly critical tissue super-saturation occurs shortly after take-off during a commercial flight; in fact, 90 min after take-off we did not find any difference in bubble grade with respect to the outgoing flight, or that immediately before take-off on the return flight.

This in-flight bubble formation could be explained in three different ways:

- Bubbles could persist in divers for a longer time than usually believed, and not be detectable by ultrasound before take-off because of their small size. Then, the in-flight decrease in ambient pressure may cause their growth and make them detectable again;
- Higher than estimated inert gas tensions could persist in the tissues for longer than believed and bubbles could be newly generated by the new supersaturation caused by flying. This could occur in predisposed subjects only or in all the divers, but the phenomenon might only be evident in the predisposed subjects;
- Genetically predisposed individuals may possess an endothelial blood vessel surface more prone to generate micronuclei and bubbles during the decompression/depressurization phase.^{19,20}

Pre-flight oxygen breathing to reduce bubble formation and/or decompression sickness incidence risk^{21,22} could be considered for bubble-prone divers to reduce the residual supersaturation of inert gas and the number of micronuclei, as previously hypothesised.²³

The authorization of the use of a medical device in flight, as in our investigation, opens new avenues for research, not only related to bubble formation but also to pathophysiological conditions which could be negatively affected by situations of mild hypoxia caused by altitude exposure in particularly predisposed subjects.^{24,25} Even though it is difficult to standardize real-life diving conditions, we believe this study provides useful data informing the safety of scuba diving. Our data suggest that 24 hours post multi-day, multiple no-decompression diving may be an insufficient delay before flying for some, bubble-prone divers. Further studies are already planned to validate our results on a larger number of subjects.

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Danilo Cialoni¹, Massimo Pieri¹, Costantino Balestra^{1,2}, and Alessandro Marroni¹

¹ DAN Europe Research Division, Roseto degli Abruzzi, Italy

² Environmental, Occupational and Ageing Physiology Lab, Haute Ecole Paul Henri Spaak, Brussels, Belgium

Address for correspondence:

Danilo Cialoni

DAN Europe

Contrada Padune 11

64026 Roseto degli

Abruzzi (TE), Italy

Phone: +39(0)85-893-0333

Fax: +39-(0)85-893-0050

E-mail: <dcialoni@daneurope.org>

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