RESEARCH ARTICLE

Flying After Diving: In-Flight Echocardiography After a Scuba Diving Week

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Introduction: Flying after diving may increase decompression sickness risk (DCS), but strong evidence indicating minimum preflight surface intervals (PFSI) is missing. ***Methods:*** On return flights after a diving week on a live-aboard, 32 divers were examined by in-flight echocardiography with the following protocol: 1) outgoing flight, no previous dive; 2) during the diving week; 3) before the return flight after a 24-h PFSI; and 4) during the return flight. ***Results:*** All divers completed similar multiple repetitive dives during the diving week. All dives were equivalent as to inert gas load and gradient factor upon surfacing. No bubbles in the right heart were found in any diver during the outgoing flight or at the preflight control after a 24-h PFSI following the diving week. A significant increase in the number and grade of bubbles was observed during the return flight. However, bubbles were only observed in 6 of the 32 divers. These six divers were the same ones who developed bubbles after every dive. ***Conclusions:*** Having observed a 24-h preflight interval, the majority of divers did not develop bubbles during altitude exposure; however it is intriguing to note that the same subjects who developed significant amounts of bubbles after every dive showed equally significant bubble grades during in-flight echocardiography notwithstanding a correct PFSI. This indicates a possible higher susceptibility to bubbles formation in certain individuals, who may need longer PFSI before altitude exposure after scuba diving.

Keywords: no-fly time, decompression sickness, post diving altitude exposure.

FLYING AFTER DIVING may increase the risk of decompression sickness (DCS) (17,18), but strong evidence indicating the minimum safety preflight surface intervals (PFSI) between diving and high altitude exposure is still missing (21,22). The first flight after diving guidelines were issued during the flying after diving workshop in 1989 (20). A minimum PFSI of 12 h after up to 2 h no-stop diving, 24 h after multiday, unlimited no-stop diving, and between 24 and 48 h after dives requiring mandatory decompression stops, was indicated (20). Following this the Divers Alert Network (DAN) initially proposed the general recommendation to wait 24 h after recreational diving, which was then changed to at least 12 h after a single no-stop dive and more than 12 h after repetitive dives, decompression dives, and multiday diving (23).

The results of a series of trials conducted by DAN between 1992 and 1999 were reported by Vann et al. (23,24), showing no DCS for surface intervals longer than 11 h after single no-stop dives and no DCS for surface intervals longer than 17 h for repetitive, no-stop dives. The authors concluded that the DCS incidence decreases as the PFSI increases. The U.S. Navy used the results from the DAN trials to revise its rules for ascent to the surface following compressed air diving (6). Pollock (19) considered PFSI approaching 24 h to be too long. Studies were also made on divers who flew with DCS and in this case, too, the odds of DCS increase as the PFSI decreases (8,9). The large number of divers who go on scuba diving holidays to tropical destinations and fly back prompted us to further investigate this topic.

Current guidelines on flying after diving suggest different PFSI for commercial, military, and recreational divers. Our interest was mainly directed to recreational divers, who are increasing in number and who present different characteristics. The current most commonly adopted indication for PFSI in recreational diving ranges from 12 to 24 h. The current guidelines indicate a minimum PFSI of 12 h after a single no-decompression dive. A minimum PFSI of 18 h is suggested after multiple dives per day or multiple days of diving, and intervals longer than 18 h are suggested after dives requiring mandatory decompression stops (23). All the above-mentioned indications are the result of chamber studies and simulated cabin pressure conditions, but there are potentially important differences between field and chamber studies and these trials might not have simulated all the conditions that occur during real flying after diving (23).

We hypothesized that inert gas accumulated during exposure to increased hyperbaric pressure may remain in the tissues for longer than the so-far estimated safe interval of 24 h after multiple multiday recreational diving. A rapid decrease of the ambient pressure may generate a further tissue super saturation that, in predisposed subjects, may in turn generate the formation of bubbles. The scope of this work was to perform Doppler

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echocardiography during real commercial flights on divers returning to their home country after 7 d of repetitive diving at a tropical dive site with a 24-h PFSI.

METHODS

Subjects

We studied a group of 32 healthy divers (23 men, 9 women); mean age 45.87 ± 13.17; mean height 173.81 cm ± 8.61; mean weight 73.87 kg ± 14.99; body mass index (BMI) 24.24 ± 3.44. All subjects were active experienced scuba divers. No subject had historical or clinical evidence of arterial hypertension, cardiac, pulmonary, or any other significant disease. All subjects were nonsmokers and had been fasting for at least 2 h before undergoing the planned tests. All dives were no decompression dives, not exceeding 45 min total dive Q1 time, and at depths not deeper than 98.4 ft (30 m), with ascent along the reef at the average ascent rate of 29.5–32.8 ft · min^{-1} (9–10 m · min^{-1}) and followed by a safety stop of 5 min at 16.4 ft (5 m).

Equipment

Transthoracic echocardiography was performed by a commercially available instrument (MyLab 5, Esaote SPA, Florence, Italy). All echocardiograms were recorded with the subjects lying on their left side and breathing normally. Ultrasound recordings were made by a technician with over 500 h recording experience in transthoracic echocardiography, bubble grade count, and evaluation. To further confirm echocardiographic findings, all subjects were also monitored for venous gas emboli using precordial Doppler ultrasound probes. The ultrasound Doppler examination was performed with a commercially available instrument (Pocket Fetal Doppler Sonoline B, Contec Medical Systems, Qinhuangdao, Hebei Province, PRC; Probe CD 3.0 Mhz) and recorded on a Philips LFH0615voice tracer.

The tests were performed on board the aircraft (Neos Boeing 767-300ER) during three different return-home flights after 7 intensive recreational diving days on a live-aboard cruise in the Maldives Archipelago. The aircraft equivalent cabin altitude during commercial flights, under normal operating conditions, is kept within 8000 ft (2400 m), according to Federal Aviation Administration indications. The cabin pressure of the aircraft was monitored every 15 min during each of the six flights, three to the Maldives and three return-home, with an iDive Pro computer (Dive System, Valpiana, Italy). The data recorded every 15 min by our device were compared with the cabin pressure value indicated by the cockpit instrument provided by Neos at the same time intervals during the six monitored flights.

Measurement Protocol

The subjects were studied by transthoracic echocardiography and precordial Doppler ultrasound with the following protocol (**Table I**):

1. Control 1: during the outgoing flight to the Maldives before any diving exposure at 30, 60, and 90 min after takeoff (mean 849 Mbar, 0.837 atm);
2. Control 2: during the diving week, on every diving day, before and at 30, 60, and 90 min after surfacing from any dive;
3. Control 3: before embarking on the return flight, after a 24-h interval from the last dive at 30, 60, and 90 min before takeoff; and
4. Test: during the return flights: at 30,60, and 90 min after takeoff (mean 849 Mbar, 0.837 atm).

It was not possible to perform tests for more than 90 min due to battery autonomy limitations, since at the moment it is not allowed to recharge batteries on board. Regarding the precordial Doppler, we used the same time intervals as for the echocardiograms.

Bubbles observed in the heart cavities during Doppler ultrasound echocardiography were graded according to the Eftedal and Brubakk scale (4) as follows:

0—no bubbles;
1—occasional bubbles;
2—at least one bubble per four heart cycles;
3—at least one bubble per cycle;
4—continuous bubbling; or
5—“white-out”: impossible to see individual bubbles.

The mean and median bubble grades after all 14 dives made during the week were calculated, separating the subjects who developed bubbles every day and after every dive (Bubblers) from subjects who developed bubbles only occasionally (Occasional Bubblers) and subjects who did not develop bubbles (Non-Bubblers) (**Table II**).

All divers filled in a questionnaire developed to collect information about age, gender, and standard anthropometric data such as height and weight, from which BMI was calculated. We also collected information about general physical fitness (habitual exercise, occasional exercise, or no exercise) and general health conditions, including heart rate, diastolic and systolic blood pressure, and vital capacity. Differences between Bubblers, Occasional Bubblers, and Non-Bubblers concerning age, height, weight, BMI, general physical fitness, heart rate, and diastolic and systolic blood pressure

TABLE I. MEASUREMENT PROTOCOL.

	Test Procedure	Timing Test
Control 1	During the flight to the Maldives (no previous diving exposure)	30, 60, & 90 min after takeoff
Control 2	During the diving week: before and after every dive	30, 60, & 90 min after surfacing
Control 3	Before boarding the return flight: after a 24-h preflight surface interval	90, 60, &30 min before to takeoff
Test in flight	During the return flight	30, 60, & 90 min after takeoff

The subjects were studied by transthoracic echocardiography and with precordial Doppler ultrasound four different times: three controls and during the return flight.

TABLE II. AVERAGE AND MEDIAN BUBBLE GRADES AFTER ALL 14 DIVES IN BUBBLERS, OCCASIONAL BUBBLERS, AND NON-BUBBLERS ON THE BOAT AND IN FLIGHT.

	Mean in Boat	Median in Boat	Mean in Flight	Median in Flight
Bubblers	2.52 ± 1.28	3.0	1.28 ± 0.83	1.0
Occasionally Bubblers	0.50 ± 0.86	0.0	0.0	0.0
Non-Bubblers	0.0	0.0	0.0	0.0
Bubblers vs. Non-Bubblers	P-value < 0.0001		P-value < 0.0001	

Difference in bubble grades was statistically significant ($P < 0.0001$).

were evaluated; vital capacity was investigated by means of a spiro-bank Mir© device (MIR Medical International Research, Rome, Italy). We also investigated if there was any difference between Bubblers, Occasional Bubblers, and Non-Bubblers and dive profiles (maximum depth, time of diving, ascent rates, safety stops, gradient factor, surface intervals). All subjects dove with their own dive computer and made compressed air dives reaching the allowed no-decompression limit. The gradient factor (GF; estimated tissue inert gas supersaturation) was calculated from the dive profile downloaded from the dive computers according to the Buehlmann Zh16 model. The percentage fraction (GM%) of the maximum allowed inert gas tissue supersaturation (M value) indicates how far the inert gas tension (T) has entered the "decompression zone." When calculated as a negative exponential function, GM% equals 0 along the total tissue saturation slope and 1 along the M value slope (i.e., 100%, which represents the maximum level allowed). GF therefore can also be computed and expressed as follows: $GM\% = (T - pP) / (M - pP) \times 100$. The GF values of the 448 dives made during the week were compared to discover any statistically significant difference. The protocol was submitted to the institutional Academic Ethical Committee (comite d'ethique hospitalier du C.H.U. Brugmann), approval No. CE 2008/66. All participants were informed about the scope and procedures of the echocardiographic examination and gave their written informed consent to the study.

Q2

Q3

Electromagnetic Interference

The safety requirements before using any electronic device on board commercial aircraft (in this case, an echocardiograph) are very stringent (11). The safety requirements of the electronic devices used in the present on-board study were cleared for in-flight use, according to EASA OPS 1.110, regulations on portable electronic devices used in aircrafts by specific pre-experiment test. These tests allowed the use of our specific device (serial Number 05-02,864) on board a Boeing 767-300ER in the specific configuration adopted by Neos Airline. The use of this specific device on different aircrafts or of different devices on a Boeing 767-300ER requires a new specific electromagnetic interference test.

Statistical Analysis

Data are presented as mean ± SD or median ± range for nonparametric data (e.g., bubble grades). The percentage of subjects who developed bubbles during the diving week and in flight was calculated. In subjects that developed bubbles ($N = 6$), differences in baseline grade and the separate bubble grades measured at different moments of the return flight were tested by means of nonparametric repeated measures analysis of variance (ANOVA Kruskal-Wallis test), followed by Dunn's post hoc multiple comparison tests. Differences in mean bubble grades between Bubblers, Occasional Bubblers, and Non-Bubblers were calculated by two-sample *t*-test after the Kolmogorov-Smirnov normality test. Differences between Bubblers, Occasional Bubblers, and Non Bubblers concerning age, height, weight, BMI, general physical fitness, heart rate, and diastolic and systolic blood pressure were calculated through repeated measures analysis of variance (ANOVA Kruskal-Wallis test). Differences between Bubblers, Occasional Bubblers, and Non-Bubblers and dive profiles (maximum depth, time of diving, ascent rates, safety stops, gradient factor, surface intervals) were also calculated using the same statistical test. Also, differences in gradient factor between subjects and differences in aircraft cabin pressure between the six flights were assessed in the same way. A probability of lower than 5% was assumed as a threshold to reject the null hypothesis ($P < 0.05$).

RESULTS

Control 1: Outgoing Flight

On the way to the Maldives before any diving exposure we did not find any bubbles in the right part of the heart in any of the subjects tested.

Control 2: During the Diving Week

During the diving week, before and after every dive on every diving day, analysis of the echocardiograms made showed that six subjects constantly developed bubbles every day and after every dive and that, of the remaining 26 subjects, 10 developed only occasional bubbles and 16 did not develop any bubbles. Difference in bubble grades among Bubblers, Occasional Bubblers, and Non-Bubblers was statistically significant ($P < 0.0001$) (Table II)

Control 3: Before the Return Flight

Immediately before the return-home flight, after a 24-h surface interval, no bubbles were found in any of the subjects studied.

Test In Flight: Test at High Altitude on the Return Flight

During the return flight, measurements were taken at three different times (30, 60, and 90 min after takeoff). Bubbles were observed in 6 of the 32 subjects (18.75%; **Fig. 1**). The in-flight bubble-positive subjects were the same who showed as positive during control 2 (post-dive testing). Interestingly, in this study, all the subjects who developed bubbles after every dive during the week of diving also developed bubbles in flight.

The mean and median bubble grades in flight were calculated, dividing Bubblers, Occasional Bubblers, and Non-Bubblers (Table II). Differences in bubble grades were statistically significant ($P < 0.0041$). Compared with bubble grades recorded before boarding the return flight (control 3) and with the data recorded during the outgoing flight, there was an increase in the grade of bubbles observed during the return flight ($P = 0.0029$); however, bubble grades decreased with the increase in flying time.

We did not find any difference between Non-Bubblers, Occasional Bubblers, or Bubblers in height ($P = 0.50$), weight ($P = 0.27$), BMI ($P = 0.95$), general physical fitness ($P = 0.58$), heart rate ($P = 0.82$); diastolic and systolic blood pressure ($P = 0.67$ and $P = 0.65$), or vital capacity ($P = 0.49$). We found a significant difference when we considered age ($P = 0.0004$). Older divers produced more bubbles that younger ones. This difference was more evident between Bubblers versus Non-Bubblers ($P = 0.0002$) than between Bubblers and Occasional Bubblers ($P = 0.02$), and we did not find this difference between Non-Bubblers and Occasional Bubblers ($P = 0.09$).

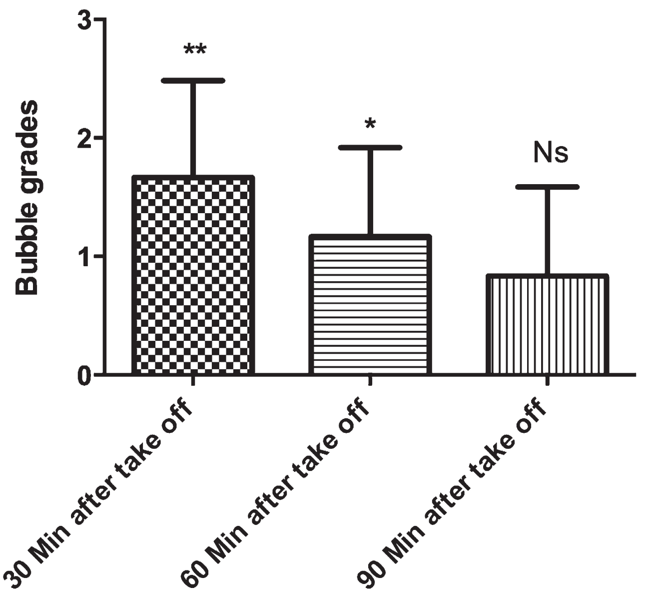

Fig. 1. Venous gas emboli evolution during flight in six divers. Difference in bubble grades between baseline (control 1 and control 3 – equal to zero) and the return flight (30, 60, and 90 min after takeoff). Ns = not significant; $*P < 0.05$; $**P < 0.01$. Note: 6 of the 32 divers developed bubbles during flight; these were the same subjects that developed bubbles every day after every dive.

We did not find any difference between bubble grades and maximum depth ($P = 0.30$; Bubblers vs. Occasional Bubblers, $P = 0.61$; and Bubbler vs. Non-Bubblers, $P = 0.89$). Similar results were found for time of diving ($P = 0.09$; Bubblers vs. Occasional Bubblers, $P = 0.79$; and Bubblers vs. Non-Bubblers, $P = 0.40$) and for surface intervals ($P = 0.39$; Bubblers vs. Occasionally Bubblers, $P > 0.99$; and Bubblers vs. Non-Bubblers, $P = 0.74$). All divers respected normal ascent rates, no diver made any extra safety deep stops, but all divers made a "normal" safety stop at 16.4 ft (5 m) for 3 min on every dive.

All divers boarded the return flight after a 24-h interval from the last dive. No difference was found in GF value (as calculated at the end of every dive) between Bubblers, Occasional Bubblers, or Non-Bubblers ($P = 0.22$). GF analysis of the 448 dives made during the week did not show any statistically significant difference ($P = 0.3622$) and none was found when comparing GF between Bubblers, Occasional Bubblers, and Non-Bubblers ($P = 0.2220$). The precordial Doppler recordings during the diving week were consistent with the echographically collected data ($P = 0.1066$). Analysis of the aircraft cabin pressure showed no statistically significant difference in the six flights (three outgoing, and three return; $P = 0.9991$).

DISCUSSION

The scope of this study was to investigate the formation of bubbles during a return flight after 1 wk of intensive recreational repetitive dives with a 24-h PFSI. To assure maximum consistency of the recorded data we designed a protocol using Doppler echocardiography in four different exposure conditions. Echo images were thus recorded during the outgoing flight and without any previous dive; after every dive during the diving week; 24 h after the last dive immediately before boarding; and during the return flight.

The results showed when a 24-h PFSI was used, the majority of the subjects did not develop bubbles during altitude exposure. However, it is intriguing to note that only the subjects who developed significant amounts of bubbles after their dives (control 2) showed equally significant bubble grades during in-flight echocardiography, but not during the preflight control after a 24-h PFSI. This data is particularly interesting if we consider that all subjects who developed bubbles every day after every dive also developed bubbles in flight.

The formation of bubbles appears to be caused by altitude exposure during flying (cabin pressure is usually between 4921.3–8005.3 ft/1500–2440 m above sea level equivalent altitude) in some but not all of the subjects who made repetitive dives during the previous days. In fact, no bubbles could be found in any subject during the outgoing flight, without any previous diving exposure (control 1), nor could we find any bubbles in any of the subjects when monitored 90, 60, and 30 min before takeoff and after a 24-h PFSI. This shows that bubbles appeared during altitude exposure, although not in all the subjects tested (control 3). This is consistent with the possibility that inert gas accumulated during exposure to increased hyperbaric pressure may remain in the tissues of certain individuals for longer than the so far estimated safe interval of 24 h after multiple multiday recreational diving.

It is also plausible that bubbles are present in divers before flight, but these bubbles are not detectable with ultrasound, indicating that bubbles may persist for a longer period than is usually believed. A rapid decrease of the ambient pressure, as happens on commercial flights, may then generate a further tissue supersaturation that in predisposed subjects may in turn generate the formation of bubbles. It should be noted that only six subjects developed bubbles every day and after every dive, and that our data shows an interesting relationship between bubblers and age; as already published, this may be due to the lesser $\dot{V}O_{2max}$ related to a reduction in physical activity with older age (25). These data require further investigation on more subjects. It is also interesting that the dive profile (in terms of computed inert gas supersaturation levels) does not appear to influence the development of bubbles, as confirmed by the GF analysis.

We observed these results during the return flight, which represents a common modality of exposure to such potential risk for many recreational divers and clients of the modern diving tourism industry, but we should not forget that similar altitude exposures, frequently with much shorter PFSI, occur when divers drive back home through mountain passes, returning from a day of diving, a very frequent occurrence in continental Europe. Our results do not, so far, justify a change in the current guidelines for safe preflight intervals and seem to confirm that 24 h of PFSI is reasonably safe after a period of intensive multiday recreational diving. However, it appears that certain individuals, particularly those who are more prone to producing significant amounts of bubbles after their recreational dives, also appear prone to producing large amounts of circulating bubbles when exposed to moderate altitude (such as in commercial flights), even if 24 h have elapsed after their last dive.

Further investigation is ongoing to investigate and monitor possible different flight conditions (cabin pressures) and PFSI. Some flights can actually reach spikes of cabin pressure as low as 708 mbar (8005.3 ft/2440 m equivalent altitude) and the current guidelines suggesting 18-h PFSI may represent an increased risk in certain bubble-prone divers, which may be conducive to reaching critical bubble levels. The absence of a correlation between GF and bubble grades, as well as the close similarity in the dive profiles used by our study subjects, seems to show the important variable favoring the development of significant amounts of circulating bubbles may be the possibility of individual predisposition. Likewise the absence of any correlation between the bubble grades and other potential risk factors, such as biometrical data or diving profile, indicate that such a possible predisposition may be due to more complex aspects. Should this hypothesis be confirmed by further studies, particularly predisposed subjects could be considered at "bubble risk" even after minimal exposure to decreased ambient pressure. For such individuals a PFSI longer than currently recommended or preoxygenation before flight may be suggested (26).

Our investigation method opens other possible research paths not only related to bubble formation (2,5), but also to pulmonary (3,7,13) and cardiac changes (14–16) induced by ambient pressure changes that frequently occur during commercial flights (1,10,12). We believe that this study can be useful both for the safety of scuba diving and to investigate other risky conditions potentially affecting nondivers during flying. Further studies are needed to validate our results on a larger number of subjects.

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Author Query sheet–ASEM3805

Q1 : Author: We normally provide both feet & meters for depth and altitude. Please check that conversions are acceptable.
Q2 : Author: Is MIR Medical International Research the correct maker of the Mir device and is Rome, Italy, the correct location for them?
Q3 : Author: Is this correct? Is GF the abbreviation for 'gradient factor'? If not, please define GF.