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# Correlation between decompression sickness and circulating bubbles in 232 divers

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Gardette, B. 1979. Correlation between decompression sickness and circulating bubbles in 232 divers. Undersea Biomed. Res. 6(1): 99–107.—Doppler monitoring examinations were carried out during 67 simulated helium-oxygen dives in the pressure chambers of the Centre d'Etudes Hyperbares (CEH) COMEX Marseille, and involved a total of 232 COMEX professional divers. Three to five detections were done in each 24-h period, each consisting of an observation at rest and an observation after deep knee bends. Recordings of the Doppler signals were subsequently analyzed by experienced listeners and graded according to the system described by Spencer and Johanson (1974). The two vestibular decompression accidents in this series were associated with bubble scores of grade 3 at rest; one occurred during the rapid initial phase of a bounce dive decompression and the other after return to the storage depth after an excursion dive. Twenty-five cases of muscular or joint pains were observed. A higher incidence of this type of problem was found with higher bubble grades in general, although it was not possible to predict pain.

decompression sickness — bubbles
Doppler detection — vestibular bends

Since the first applications of Doppler ultrasound bubble detection, described by Spencer and Campbell (1968), Smith and Johanson (1970), and Smith and Spencer (1970), the technique has been widely used in conjunction with decompression. As a research tool, it has been adapted for use with transducers implanted in experimental animals (Evans and Walder 1970; Guillerm, Masurel, and Monjaret 1973; Guillerm, Masurel, Guillaud, and Monjaret 1975). However, it is in the mode of transcutaneous bubble detection with human subjects that the apparatus has found its widest and probably most useful application (Guillerm et al. 1975; Masurel, Guillerm, and Cavenel 1976; Gardette, Lemaire, and Dumas 1977; Masurel, Gras, Gardette, Ternisien, and Guillerm 1977). This report summarizes the results from more than 2000 observations carried out during the decompression phases of helium-oxygen dives at the Centre Experimental Hyperbare of COMEX in Marseilles. Data on decompression incidents and accidents were assembled with the aim of observing the correlation between the grade of circulating bubbles and the occurrence of clinical decompression sickness.

## METHODS

### The dives

Bubble detection was carried out during 67 simulated helium-oxygen dives in the pressure chambers of the Centre Experimental Hyperbare; 232 subjects were involved. Bounce dives, excursion dives, and saturation dives were conducted. Depths ranged from 35 to 480 meters, and bottom times were as short as 30 min and as long as 8 days. This information is summarized in Table 1. Fifty-seven of the dives included decompressions of an experimental nature that were part of the formulation of a new series of COMEX decompression tables. Only those dives labeled 'COMEX Saturations' had decompressions that are currently utilized on COMEX operational worksites.

### The subjects

Experimental subjects were COMEX professional divers who had been certified as medically fit for deep diving and were in good physical condition at the time of their dives. Mean age was 28.3 ± 4.5 years, mean height was 1.75 ± 0.7 meters, and mean weight was 72.3 ± 8.8 kilograms.

### Bubble detection

To observe circulating bubbles, a device using the Doppler effect was employed. It was developed by the Institut National des Sciences Appliquées in Lyon (Professor Guillaud) in cooperation with the Centre d'Etudes et de Recherches Techniques Sous-Marines in Toulon (Dr. Guillerm), and the researchers of the Centre Hyperbare of COMEX in Marseilles. The device, fabricated by SODELEC S.A. of Marseilles, consisted of three main elements. First, the transducer was built around two piezoelectric ceramics and was designed to be placed on the chest in the precordial area. The major components of the device were a 5-MHz quartz oscillator for the output mode and processing circuits for the reception mode. The resulting signal can then be channelled into the operator's earphones, and may also be recorded on tape.

All subjects were trained to position the transducer to obtain the optimal audio signal in the precordial region. In every 24-h period, three to five bubble detections were accomplished per

**TABLE 1**
CHARACTERISTICS OF 67 DIVES MONITORED BY DOPPLER

| COMEX $He\text{-}O_2$ Dives | No. Dives | No. Subjects | Depth, msw | Bottom Time |
|---|---|---|---|---|
| Bounce | 25 | 68 | 66 - 210 | 30 - 150 min |
| Excursion (Janus IV) | 13 | 39 | 480, 460 - 400 | 3 - 6 h |
| Saturation COMEX | 10 | 61 | 150 - 300 | 24 - 36 h |
| Experimental Decompression | 19 | 64 | 35 - 400 | 4 h - 8 days |
| Total | 67 | 232 | | |

subject; one of these consisted of a control observation before beginning the dive. Each session consisted of a recording with the subject first in a relaxed standing position, and then again after performing a series of two or three deep knee bends spaced 30 s apart. These movements served to release bubbles. For example, a grade 1 bubble observed in a subject at rest becomes a grade 2 or 3 bubble after movement. The tapes of the bubble signals were subsequently analyzed by experienced listeners and graded according to the system described by Spencer and Johanson (1974) and by Spencer, Johanson and Campbell (1976).

## RESULTS

The level of circulating bubbles could be related to two types of decompression accidents, namely vestibular bends (2 cases) and muscle or joint pains (25 cases). Since two different pathophysiologic phenomena seem to be involved, the results are presented separately.

### Vestibular bends

The first incident occurred during the rapid initial phase of decompression from a bounce dive of 120 min at 210 m (Fig. 1). Three subjects participated in the dive. Three hours and 20 minutes after the start of the decompression, at a depth of 103 m, subject *JPP* presented with the following signs and symptoms: intense vertigo that prevented him from standing upright, headache, nausea, and slight spontaneous nystagmus in the horizontal plane; his hearing was unaffected. A few minutes before the onset of these characteristic signs, grade 3 bubbles were monitored at rest in this subject. Therapeutic recompression of 30 m and appropriate medication eradicated all symptoms. Neither of the two other divers had any symptoms of an accident, although *PJ* registered a grade 2 at rest and a grade 3 with movement (Fig. 2).

The second case of vestibular decompression sickness occurred in subject *JMK* during decompression from an excursion dive (460–400 m) in the laboratory simulation phase (Phase II) in preparation for the JANUS IV open-sea dive (Fig. 3). The excursion dive consisted of 60 min of compression from 400 to 460 m, 3 h and 33 min at 460 m, and a decompression of 58 min to 400 m.

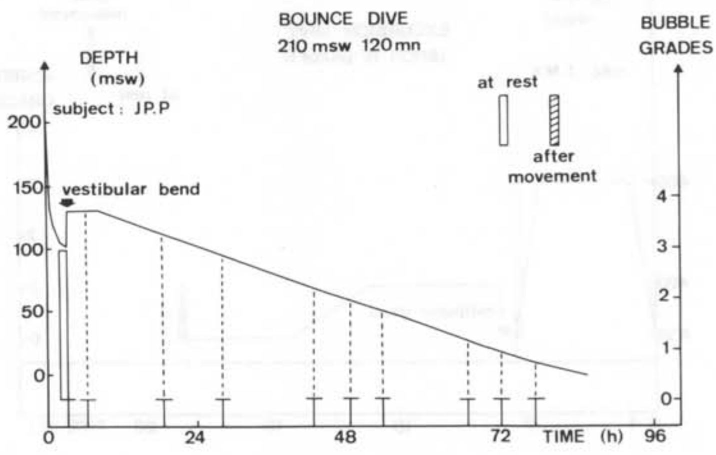


Fig. 1. Profile of 210 msw, 120 min bounce dive, showing bubble scores and occurrence of vestibular decompression sickness, subject *JPP*.

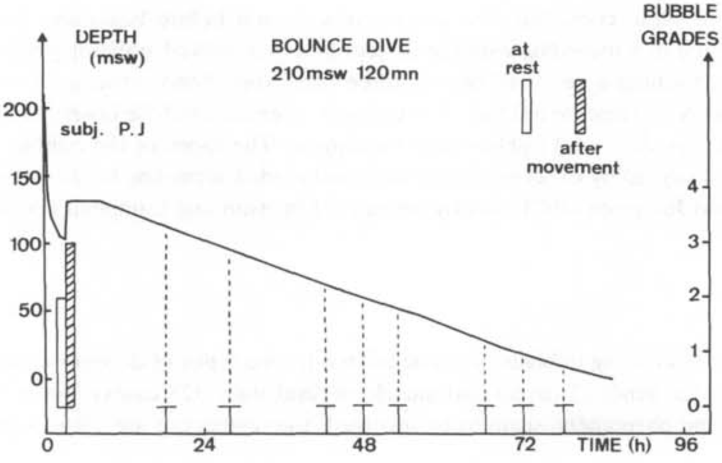


Fig. 2. Profile of 210 msw, 120 min bounce dive, showing bubble scores for subject *PJ*.

Thirty minutes after returning to the storage depth, the subject began to show the same symptoms of vestibular problems as those in the previous case. Roughly 15 min before the accident, the subject had registered grade 3 bubbles at rest. Therapeutic recompression of 20 m (to 420 m), accompanied by medication and breathing a hyperoxic mixture ($Po_2$ = 1 bar) led to complete resolution of the vestibular signs. The subject's two companions gave no indication of any problems and they were also free of any detectable bubbles.

In Table 2, an attempt has been made to correlate the occurrence of these two accidents with the level of bubbles detected by Doppler monitoring during the excursion and bounce dives. The results are expressed as follows: the numerator is the number of subjects manifesting vestibular accidents, and the denominator shows the number of subjects who had *maximum bubble levels* corresponding to the grade shown. No vestibular accidents occurred during saturation dives.

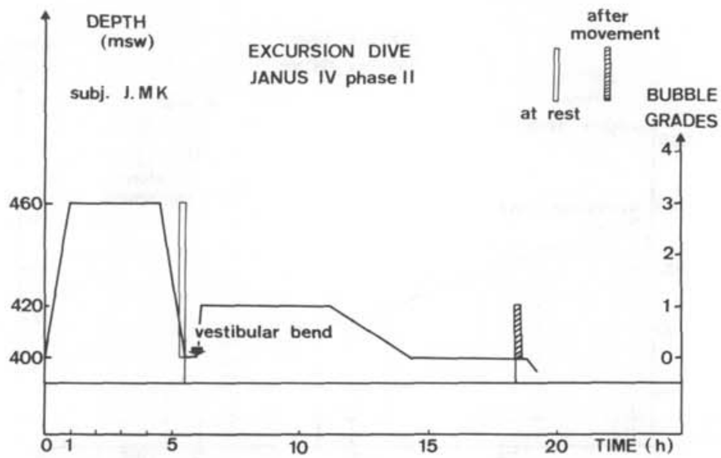


Fig. 3. Profile of Janus IV excursion dive, showing bubble grades and vestibular incident, subject *JMK*.

**TABLE 2**

Correlation Between Vestibular Decompression Sickness and Circulating Bubbles During Fast Phase of Decompression

| | At Rest | | | | | After Movement | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bubble Grades | 0 | 1 | 2 | 3 | 4 | 0 | 1 | 2 | 3 | 4 |
| Bounce Dives | 0/62 | 0/2 | 0/3 | 1/1 | 0/0 | 0/51 | 0/8 | 0/4 | 1/5 | 0/0 |
| Excursion Dives (Janus IV) | 0/35 | 0/0 | 0/2 | 1/2 | 0/0 | 0/31 | 0/3 | 0/1 | 0/2 | 1/2 |
| Total | 0/97 | 0/2 | 0/5 | 2/3 | 0/0 | 0/82 | 0/11 | 0/5 | 1/7 | 1/2 |

From this table it is apparent that the two vestibular accidents were preceded by high levels of circulating bubbles at rest (grade 3 on the Spencer scale). Despite the small number of cases, it can be inferred that such a bubble score at rest indicates a high risk of vestibular accident (2/3) when such a score occurs during the rapid initial phase of a bounce dive decompression or in association with return to storage depth after an excursion dive. On the other hand, no vestibular accidents occurred among 107 subjects with bubble grades 0, 1, or 2.

Moreover, it can be seen that the vestibular victims had high bubble grade levels with movement (grade 3 in the bounce dive incident and grade 4 in the excursion dive case). For all the cases, however, bubble scores during movement indicated less risk than bubbles at rest.

**Muscle or joint pains**

Of the 25 cases observed, only two required therapeutic recompression: the other pains had the characteristics of arthralgia rather than articular bends. Two accidents occurred during decompressions from helium-oxygen bounce dives, and 23 during decompressions from saturation. In the majority of cases, the accidents occurred in the final stages of decompression, whatever the bottom depth of the dive; the mean depth of onset was 10.4 ± 7 m. In association with these 25 cases of muscle or joint pains, bubbles in varying degrees were detected.

For example, as shown in Fig. 4, moderate bubble levels increased gradually to grade 3 with movement and were followed by pain. As shown in Fig. 5, subject *JMK* had a bubble grade of 3 during movement throughout almost the entire 9-day decompression; he dropped to a grade 2 during movement the last two days and then he developed pain. The opposite extreme is represented by the subject shown in Fig. 6. Despite a grade 0 at rest and with movement throughout the decompression, subject *FR* had a decompression sickness accident just before surfacing.

Table 3 is a summary of the results for pain incidence related to bubble grade. The numerators and denominators represent the same variables as in Table 2; percentage values are also given in this table. The results are grouped according to type of dive, with bounce dives and excursion dives separated from saturation dives, during which the majority of accidents occurred. From this table, it can be seen that although there were only two pain-only incidents in the bounce and excursion dive group, a grade 0 at rest was associated with an accident in only about 1% of cases. On the other hand, for saturation decompression, a grade 0

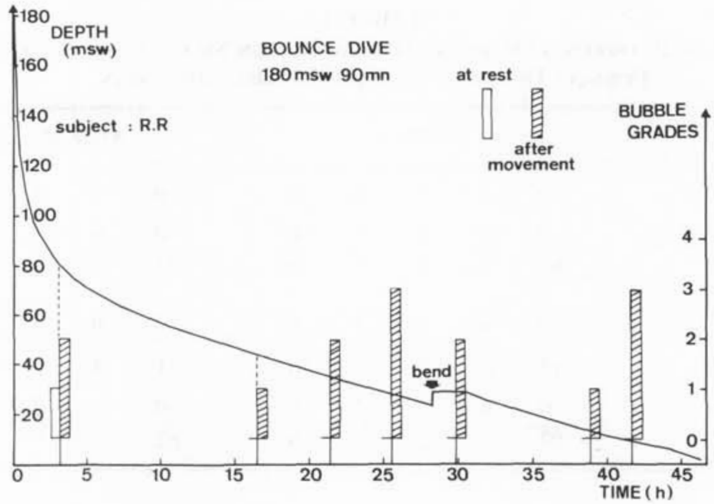


Fig. 4. Profile of 180 msw, 90 min bounce dive, showing bubble grades and pain-only decompression sickness incident, subject *RR*.

at rest was associated with a significant (14%) incidence of pain. A grade 1 at rest was the highest bubble score monitored in 16 divers decompressing from saturation; of these, 6 or 37% had accidents.

This difference according to type of dive was also evident when bubble grade during movement was considered. Again, a grade 0 during movement was related to an incidence of approximately 1% in the bounce and excursion dive group, and the results were not significant for bubble grades 1, 2, and 3. In the saturation diving group, the percentage of accidents mounted with increasing bubble grade. Even a score of grade 0 during movement was associated with a 10% incidence of pain, and higher percentages were found when more bubbles were heard.

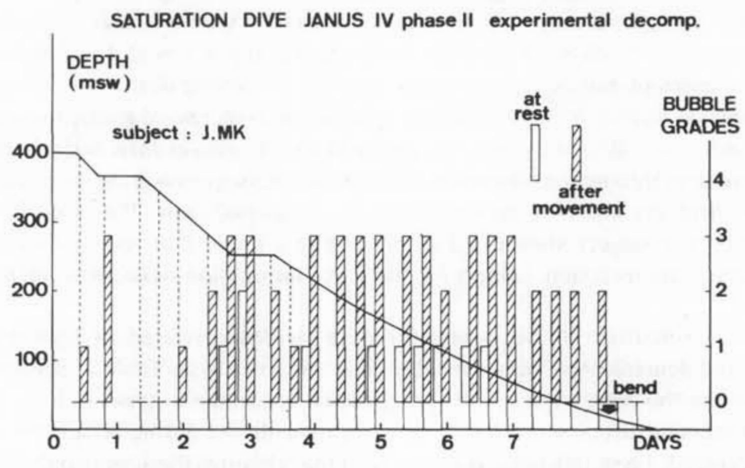


Fig. 5. Experimental decompression from Janus IV saturation dive, showing bubble scores and pain-only decompression sickness, subject *JMK*.

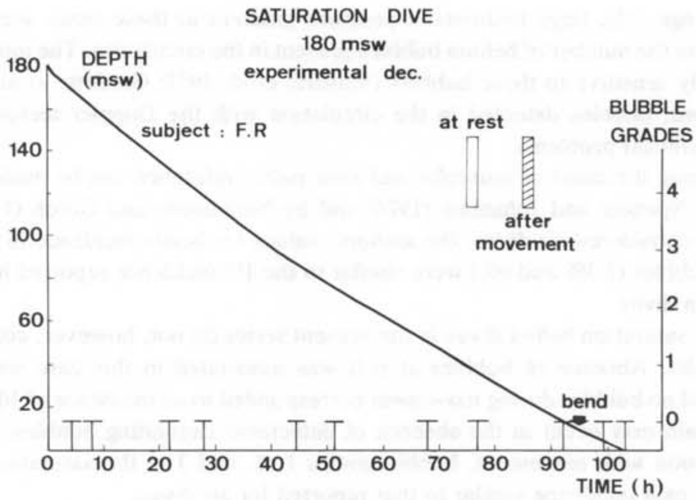


Fig. 6. Experimental decompression from saturation dive, showing bubble grade and pain-only incident.

**TABLE 3**

Correlation Between Articular or Muscular Pains and Circulating Bubbles

| | At Rest | | | | | After Movement | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bubble Grades | 0 | 1 | 2 | 3 | 4 | 0 | 1 | 2 | 3 | 4 |
| Bounce and Excursion Dives | 1/97 | 1/2 | 0/5 | 0/3 | 0/0 | 1/82 | 0/11 | 0/5 | 1/7 | 0/2 |
| % | 1 | - | - | - | - | 1 | 0 | - | 14 | - |
| Saturation Dives | 15/104 | 6/16 | 2/5 | 0/0 | 0/0 | 5/51 | 4/29 | 4/16 | 10/29 | 0/0 |
| % | 14 | 37 | - | - | - | 10 | 14 | 25 | 34 | - |
| Total | 16/201 | 7/18 | 2/10 | 0/3 | 0/0 | 6/133 | 4/40 | 4/21 | 11/36 | 0/2 |
| % | 8 | 30 | - | - | - | 4 | 10 | 19 | 31 | - |

## DISCUSSION

The two types of accidents lead to different conclusions about the predictive capability of Doppler monitoring. The results presented here are based on a large but finite sample, and therefore the values given represent only this experiment. More data will be necessary to accomplish the statistical analysis necessary to predict the risk of a future accident.

In all cases of bubble detection, we observed higher bubble grades after movement than at rest. Movement evidently served to mobilize stationary intravascular bubbles. The two cases of vestibular decompression sickness that were observed occurred during the phases of rapid pressure change. The large hydrostatic pressure gradient at these times seemed to have a direct effect on the number of helium bubbles present in the circulation. The inner ear seems to be particularly sensitive to these bubbles (Masurel et al. 1977; Gardette et al. 1977). In this case, therefore, bubbles detected in the circulation with the Doppler technique may be a predictor of clinical problems.

In considering the cases of muscular and joint pains, reference can be made to the results published by Spencer and Johanson (1974) and by Nashimoto and Gotoh (1978). Although these papers considered air dives, the authors' values for bends incidence in the absence of circulating bubbles (1.3% and 0%) were similar to the 1% incidence reported here for bounce and excursion dives.

Results for saturation heliox dives in the present series do not, however, compare with the air dive results. Absence of bubbles at rest was associated in this case with a 14% pain incidence, and no bubbles during movement corresponded to an incidence of 10%. It therefore seems that pain may occur in the absence of detectable circulating bubbles. In considering bubble detection with movement, bubble grades 1, 2, and 3 in the saturation group corresponded to a pain incidence similar to that reported for air dives.

Another observation from this experimental series is that depth did play a role in the incidence of pain, with bubbles near the end of decompression being less noxious than those during the beginning or middle of decompression. For saturation decompressions, grade 1, 2, and 3 bubbles detected during movement at less than 20% of the bottom depth were associated with a pain incidence of only 6.6%, 16%, and 20%, respectively.

From these results, it seems reasonable to hypothesize that pain during decompressions from bounce or excursion dives is directly related to the high levels of circulating bubbles that can be detected by the Doppler technique. For saturation decompressions, the situation is different. Perhaps the bubbles causing pain in this situation are too small to be detected by the Doppler device, or the accidents could be the result of stationary or extravascular bubbles. Such "silent" bubbles are all the more dangerous when they form early, whether in the beginning of a decompression or during repetitive excursion dives (Gardette et al. 1977). These bubbles are not eliminated, and they expand according to Boyle's law to cause the eventual occlusion of tissue capillaries.

Because such a good correlation was found between circulating bubbles and serious vestibular accidents, an important recommendation can be made. High grade bubbles at rest during the initial rapid phase of a decompression or during decompression from an excursion dive indicate a high likelihood of a vestibular decompression accident. Immediate preventive measures, such as recompression, are necessary whenever this situation occurs. Lower levels of bubbles at rest call for vigilance and continued monitoring because the bubble grade may increase rapidly.

Unfortunately, for saturation decompression the correlation between circulating bubbles and decompression sickness was less satisfactory for muscular and joint pains. Pain could occur during the end of a decompression in the total absence of detectable circulating bubbles.

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Gardette, B. 1979. Correlation entre les accidents de decompression et les bulles circulantes chez 232 plongeurs. Undersea Biomed. Res. 6(1): 99–107.—Des détections Doppler de bulles ont été réalisées durant 67 plongées simulées hélium-oxygène dans les caissons du Centre d'Etudes Hyperbares (CEH) COMEX Marseille, au total 232 plongeurs professionnels COMEX ont été examinés. Trois à cinq détections ont été réalisées chaque jour, chacune consistant à une détection au repos et une autre après flexions complètes sur les génoux. Les enregistrements des signaux Doppler ont été analysés et quantifiés par les expérimentateurs suivant le code décrit par Spencer et Johanson (1974). Les deux accidents vestibulaires observés furent associés à un degré 3 de bulle au repos; un accident survenant durant la phase rapide de la décompression d'une plongée unitaire et l'autre au retour au niveau vie après une plongée excursion. 25 cas de douleurs articulaires ou musculaires ont été observés. La fréquence de ces accidents augmentent avec le degré de bulle sans toutefois qu'il soit possible de prédire l'accident.

accident de décompression — bulles
détection Doppler — accidents vestibulaires

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