Dissolved Nitrogen and Bends in Oxygen-Nitrogen Mixtures During Exercise at Decreased Pressures

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Four types of simulated orbiting laboratory flights of 10 to 21 hours' duration, involving 107 man-flights and 93 analyses of N_2 dissolved in blood, were performed for the purpose of ascertaining the average intensity and duration of bends pains. Generally bends occurred most often during transfer and reconnaissance. Once bends appeared it reoccurred in subsequent flight stages. This can be avoided by sufficient breathing of O_2 such that blood N_2 falls to levels insufficient, theoretically, to provide enough N_2 molecules to form seed bubbles. On this basis it can be predicted that missions in a pure O_2 environment require 120 minutes of O_2 breathing at 14.5 psia before decompression to 5 psia and an additional 375 minutes before a second decompression to 3.5 psia. At that time one could return to 5 psia O_2 or preferably to 46:50::O_2:N_2 at 7 psia; the latter takes 33 minutes of O_2 breathing before reconnoitering at 3.5 psia. If pressure suits and locks operated successfully at 5 instead of 3.5 psia, O_2 breathing time could be saved and danger of bends avoided.

MANNING of an orbiting space laboratory depends, among other things, on success in avoiding flyer's bends. There are two periods during which pilots in "pressure suits" will be especially susceptible to bends. The first is during transfer to a laboratory, the second is during reconnaissance. This susceptibility is brought about because of the need to make physical exertions while at the same time experiencing a decompression. Although this belief is generally supported by the older literature reviewed by Haymaker[20], few studies have dealt with adequate numbers of men exposed to conditions which are being considered for orbiting laboratories.

The scarcity of needed information is a challenge to devise experiments of varying duration in precisely controlled gas mixtures and to include detailed measurements of each subject. Gas chromatography has developed to the point where nitrogen dissolved in the bloodstream can be measured specifically and accurately.[11,22] Only recently the solubility of nitrogen and other inert gases in extracted human body fat was described using this method[21]. In 1943 the status of flyer's bends with reference to obesity was reported on the basis of weight and height.[13] At that time it had just been proved that weight and height did not necessarily reflect the true quantity of body fat.[5] Since then convenient methods have been devised for the repeated measurement of gross body composition.[3] Gaseous environments in the Altitude Laboratory at this station can now be controlled economically and in accordance with desired temperature, pressure and composition. This obviates the necessity of prolonged breathing through a mask or of purging a low pressure chamber and wasting enormous volumes of gases.

Despite improved opportunities for observing bends little thought has been given to intensity and duration relationships of symptoms. Few, if any, attempts have been made to consider, let alone quantify, the effects of bends on locomotion and performance, although this has been excellently done with small animals[27]. There appears to be no ideally objective means of ascertaining the levels of severity of human bends except should there be a breakdown in the physiologic function of the cardiovascular and nervous systems. In such cases the recommended treatment is pressurization[9,10], followed by recently validated stages of oxygen inhalation and depressurization[12].

Once there were many cases of flyer's bends. A single laboratory during one year handled 858 severe cases, among which 111 were complicated by postflight circulatory reactions[14]. In his review on "dysbarism," Adler[2] cites six laboratories with 747 cases of bends in 3,754 tests performed during intermittent exercise at low pressures. These findings are typical of numerous others then made. Except for contemplation of the older data there since have been lamentably few experiments. Within the past seven years a total of 46 men have been observed by Marbarger, Balke, Damato, et al. (discussed below), who are among the first to show an interest in bends and selection of aerospace physiologic environments. This report describes progress in bends experiments, starting with 32 men who were subjected to a set of four simulated flights lasting from 10 to 21 hours. Generally bends occurred most often during transfer and reconnaissance at 3.5 psia but this could be avoided by sufficient breathing of oxygen. In order to discuss the influence of various factors it is proposed that the following are of importance in the formation of microscopic seed bubbles:

1. Surface tension of blood.
2. Change in pressure, together with the pressure equivalent effect of exercise.
3. Level of dissolved nitrogen in blood with rates of elimination and accumulation.

From this arises a general hypothesis by means of which it becomes possible, for example, to state the time required for breathing of oxygen in order to avoid bends at low pressures. With regard to the pain of bends and its localization a description of the blood

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and nerve supply of joints shows richness of blood capillary loops and tufts in the synovial membrane, together with "an abundance of free nerve-endings presumably subserving pain"[8]. Perhaps seed bubbles grow, coalesce and either lodge or, even while passing these capillary loops, cause nerve-endings to be excited. Thus, through pain the onset of yet more danger[20] for life is signaled.

MATERIALS AND METHODS

Subjects—Age, height and weights of fat and lean body are listed in Table I for men chiefly employed as

TABLE I. AGE AND BODY DIMENSIONS

Subject	Age year	Height cm.	Fat kg.	Lean kg.	Subject	Age year	Height cm.	Fat kg.	Lean kg.
1	21	178	15.4	55.9	17	29	176	22.9	50.6
2	46	168	20.0	50.5	18	27	172.5	6.7	63.4
3	39	171.5	19.3	51.9	19	37	168.5	17.5	47.4
4	30	184	14.6	73.3	20	24	180	11.2	63.1
5	36	179.5	14.6	53.3	21	30	169.5	6.9	55.8
6	24	173.5	26.3	52.8	22	36	175	14.8	62.0
7	26	187	24.5	65.4	23	21	181.5	30.8	59.3
8	28	188	19.2	67.8	24	32	169.5	22.6	47.4
9	23	184	21.8	63.3	25	19	166.5	16.5	48.8
10	24	184	9.6	55.8	26	40	179.5	15.5	33.8
11	34	175.5	12.3	60.9	27	36	185.5	15.4	65.3
12	34	173.5	17.6	49.7	28	35	172.5	14.9	53.7
13	33	185	18.9	54.4	29	35	170	25.6	55.9
14	27	186.5	20.3	63.9	30	34	177	20.3	54.6
15	31	169.5	21.7	54.3	31	24	178	19.6	56.9
16	30	181.1	11.5	63.4	32	21	166.5	18.5	48.3

flight medical officers, physiological training officers and specialists, scientists and administrators. All had passed a Flying Class III physical examination, meaning extraordinary health, were skilled with O_2 equipment and experienced in working at low pressures. On successive days measurements of body volume, residual lung volume and body weight were taken for calculation of body fat.[3]

Simulated flights — The simulated flights started with the breathing of O_2 through an aviator's mask at ambient pressures for this elevation of 14.5 psia. As shown in Figure 1 this continued for either 1.5 or 4 hours. The pressure was then decreased within 2.3 minutes to 5 psia for 2.5 hours, at which time the pressure was again decreased within 1.6 minutes to 3.5 psia. Beginning immediately, at 3.5 psia, three sets of five deep knee bends and five push-ups were performed at five-minute intervals, thus, perhaps, simulating the exertion of transfer.

The fourth stage (Figure 1) involved 4 or 12 hours of exposure in "shirtsleeves" to the gaseous environments described in Table II. In the four flights the fractional

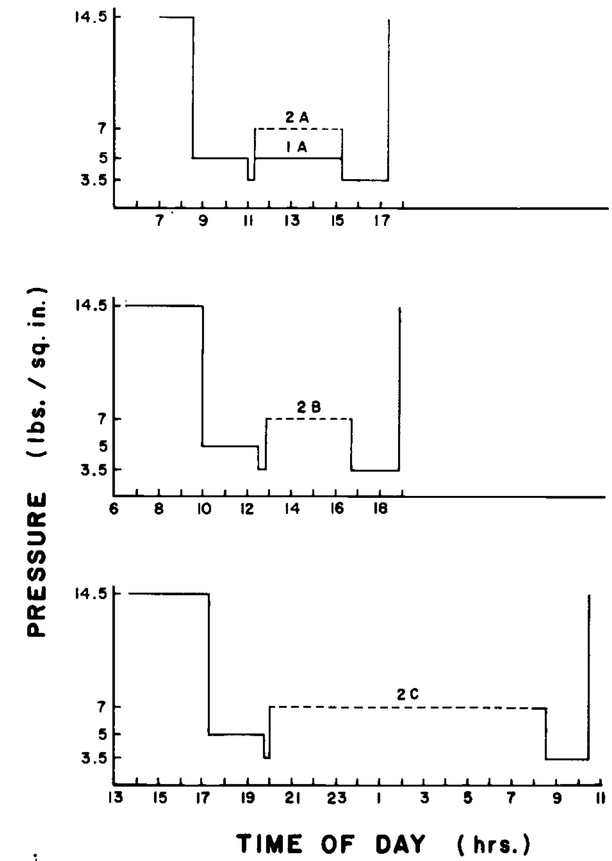

Fig. 1. Sequence of pressure stages in four types of simulated flights (*line*, breathing of pure O_2 with the body exposed to air or complete exposure to 95:1::O_2:N_2; *dashed line*, complete exposure to 46:50::O_2:N_2).

composition of water vapor and CO_2 was close to 0.041. Oxygen was 0.949 in Flight 1a with scarcely any N_2, whereas in Flights 2a, 2b, and 2c the fraction of N_2 was 0.503 and that of O_2 was 0.457. Although between the third and fourth stages less than two minutes were spent to reach the desired total pressure it took 10 minutes to achieve the desired composition. Total pressure (Table II) was automatically controlled and for all 29 runs this varied by less than 0.7 per cent. Variation in temperature influenced that calculated for water vapor. CO_2 levels rose and fell intermittently depending chiefly but not entirely on removal with Baralyme. A polarographic O_2 sensor[26] was used throughout to detect oxygen in an automatic, feedback system for controlling influx of O_2. All runs in Flight 1a were thus controlled within close limits. In other flights (especially 2c) the control within each run was equally precise; however, among runs there was more

TABLE II. MEAN (μ) AND STANDARD DEVIATION (σ) OF TEMPERATURE (°C) AND INDICATED PRESSURES (mm. Hg) IN SIMULATED ORBITING LABORATORY

Flight type	Determinations No.	Temperature μ	Temperature σ	P_{H_2O} μ	P_{H_2O} σ	P_{CO_2} μ	P_{CO_2} σ	P_{O_2} μ	P_{O_2} σ	P_{N_2} μ	P_{N_2} σ	P total μ	P total σ
1a	50	24.5	2.9	8.5	3.4	2.7	2.3	245.5	2.60	1.9	1.72	257.9	0.72
2a	30*	26.1	2.3	13.7	5.7	2.6	2.1	167.4	3.70	180.4	6.51	364.4	1.76
2b	22†	24.3	6.2	11.5	6.1	2.4	0.9	165.3	9.60	186.0	5.30	365.1	1.27
2c	88	23.4	2.8	12.3	7.7	1.6	1.6	166.8	13.60	183.3	19.30	364.9	0.76

*27 determinations of temperature.
†19 determinations of N_2 and O_2.

variation, which accounts for the larger deviations in partial pressures of O_2 and N_2. At one-hour intervals Micro-Scholander determinations (Table II, column 2) were made for CO_2 and O_2 for the "two-gas" flights (2a, 2b, and 2c); P_{N_2} includes traces of other inert gases. A Lira CO_2 meter and a Waters N_2 analyzer were used for Flight 1a, the P_{O_2} being read directly from the O_2 sensor.

While the men were in the "laboratory" their time was spent in sedentary activities—reading and writing, watching films and television, card playing, helping to calibrate instruments, coffee drinking, eating and sleeping in bunks. A commercially available, palatable liquid-food was taken at noon in the short flights, while during the evening of the long flight a hot "TV dinner" was consumed. Various personal requirements called for use of a lock at that time for transfer of materials. This was a source of slight, transient variation in the gaseous environment.

The fifth and final stage of each flight lasted two hours, during which the pressure, within 2 to 3 minutes, was reduced to 3.5 psia and the same exercises were performed except at 15-minute intervals. Oxygen masks were donned at the start of this stage and used throughout the end of Flights 2a and 2b. In Flight 2c, following the 12 hours and for 0.5 hour before decreasing the pressure, O_2 was breathed through a mask so as to remove some of the reaccumulated N_2 before exercising at 3.5 psia. The only stage of Flight 1a during which O_2 masks were used was in the first stage while at 14.5 psia.

Blood samples — A recently described, versatile gas chromatographic method was used to determine low levels of N_2[22]. Blood was taken, without stasis, from antecubital veins with precautions to avoid air bubbles. Analyses were completed within three hours. A total of 93 samples were analyzed, 17 being from collections at ambient pressures of 14.5 psia while breathing air; 31 at 14.5 psia while breathing O_2 for 0.5, 1, 2, and 4 hours; 29 at 7 psia while breathing the $P_{N_2} = 183$ mm. Hg mixture for 2, 4 and 12 hours; and 16 immediately after these preceding 12 hours and following the breathing of O_2 for 0.5 hour while at 7 psia and before going to 3.5 psia.

Bends level — Decompression sickness symptoms were reported as to onset, intensity, duration and location. Bends were recorded as grade 1 if the pain was transient and mild, grade 2 if the pain was moderate and constant but exercises could be continued and grade 3 if the pain became too intense to remain at altitude and continue exercising. When grade 3 pain occurred that man was immediately removed from the chamber through a lock. Except for one subject, and possibly two others, the grade 3 pains abated at approximately 5.5 psia and had disappeared on arrival at 14.5 psia. Even so, observations for persistent pain and neurocirculatory symptoms were continued. A hyperbaric chamber was in readiness for each flight but it was unnecessary to use this for treatment since severe, persistent reactions never occurred.

The records on each subject were analyzed in accordance with the time at each stage of a flight during which a certain grade of pain was present. An example should make this clear. Suppose on arrival at 3.5 psia there was no pain for four minutes, followed by two minutes of grade 1 pain in one or more joints, then by

TABLE III. AVERAGE GRADE OF BENDS FOR STAGES IN FOUR TYPES (1a, 2a, 2b, and 2c) OF SIMULATED AEROSPACE FLIGHTS†

	1a				2a				2b	2c	
Subject	Orbit	Transfer	Lab.	Reconnaissance	Orbit	Transfer	Lab.	Reconnaissance	Reconnaissance	Transfer	Reconnaissance
16	1.22	2.00	2.00	*2.04	0.41	1.00	0	1.07	0.99	0	0
24	—	—	—	—	0	0.69	0	1.00	0	0	0
12	—	—	—	—	0	0.61	0	*2.20	—	0	0
9	0	0	0	0	0	0.54	0	*2.07	0	0	0
8	*0.47	—	—	—	0	0.46	0	2.00	—	0	0
17	—	—	—	—	0	0.38	0	*2.15	—	—	—
1	1.35	2.00	*2.03	—	0	0.15	0	2.00	*1.68	0.31	*2.25
19	1.22	2.00	2.00	*3.00	0	0.15	0	1.00	0	0	0
3	0	0	0.11	0.75	0	0	0	1.90	1.00	0	0
32	0	0	0	0.38	0	0	0	1.53	0	0	0
2	0	0	0	0	0	0	0	1.12	0	0	0
23	—	—	—	—	0	0	0	1.07	0.60	0	0
5	0	0	0.38	*2.14	0	0	0	0.97	0	0	0
13	—	—	—	—	0	0	0	0.92	—	0	0
31	0	0	0	0.98	0	0	0	0.90	0	0	0
27	0	0	0	0.85	0	0	0	0.76	0	0	0
26	0	0	0.06	1.96	0	0	0	0.75	0	0	0
6	0	0	0	0	0	0	0	0.58	0.71	0	0
14	—	—	—	—	0	0	0	0.14	—	0	0
11	0	0	0.15	*2.25	0	0	0	0	—	0	0
28	0	0	0	0	0	0	0	0	0.54	0	0
18	0	0.77	0	0	0	0	0	0	0	0	0
21	0	0	0	1.00	0	0	0	0	0	0	0
n	22	21	21	20	31	31	31	31	24	30	30
$\bar{X}$	0.194	0.322	0.320	0.768	0.013	0.128	0.00	0.778	0.230	0.010	0.075
n′	22	18	17	13	31	30	23	23	24	30	29
$\bar{X}'$	0.194	0.043	0.041	0.247	0.013	0.099	0.00	0.463	0.230	0.010	0.00

*Grade 3 bends.

†Subjects Nos. 4, 7, 10, 22, and 30 never reported bends at any stage of the four flights; subjects Nos. 15, 20, 25, and 29 took flights 2a, 2b, and 2c only and never reported bends.

three minutes of grade 2 pain and finally by report of grade 3 pain, following which, within one minute, the subject was removed in a lock. Multiplying and taking a sum gives $4 \times 0 + 2 \times 1 + 3 \times 2 + 1 \times 3 = 11$ grade $\times$ minutes for a total of 10 minutes, for an average grade level of 1.1. Wide ranges in onset and duration of all recognized grades of pain can thus be compared with the total time set for accomplishment of successive stages of a simulated aerospace flight. For all subjects the average interval between flights was two months, and only with two subjects were flights made within one week. The only subject (No. 11) tested twice for the same flight, in the fourth stage of Flight 1a, scored grades of 0.15 and 0.21 and, in the fifth stage, scored 2.25 and 2.14. Close agreement in "bends level" occurred even though the previous reports of pain could scarcely have been recalled by either subject 14 or the observer (EAD in all instances except when serving as subject 16).

RESULTS

Almost 90 per cent of the symptoms were referred to knee or knee and ankle joints. Once pain was reported it generally became more intense, remaining at the same locations and reoccurrring during subsequent stages. Among the 31 subjects of Flight 2a the results on those suffering bends are listed according to the flight stage and then with reference to the level of bends (Table III, columns and lines respectively). Although bends were not reported in the "laboratory" stage of this flight, each of the eight men who suffered during transfer had a higher level of bends while reconnoitering. The other flights also had progressive increases in level of bends. In order to show the average intensity and duration of bends caused by *each stage* of a flight, it was decided to remove from consideration those who reported bends in preceding stages. Thus, in the first stage of Flight 2a there were 31 men with a total bends level of only 0.41, entirely due to subject 16. Deducting this subject leaves 30 men in the next stage, of whom seven reported a total grade of 2.98 for an average bends level of 0.0993. The numbers and conditional means listed in the final two lines (Table III) were obtained by this method of elimination, permitting comparison of effects of different flight stages.

The first "orbiting" stage of 1a showed a higher level of bends than that of 2a. Aside from loss of indicated subjects by a single refusal and by departure from this station the only difference was that in 1a for this stage onward the flight was in "shirtsleeves," thus permitting more freedom of movement than in 2a, where O_2 masks were used except in the "laboratory." An important difference between the two flights was the protective effect of the 7 psia as opposed to the 5 psia pressure. On the other hand, during reconnaissance only four new cases appeared in 1a as compared with 11 new cases in 2a. Longer prebreathing of O_2 was beneficial, since bends were not reported in the first three orbiting stages of 2b and only appeared in the final stage. Removal from consideration of subject 1 for preceding bends showed that one-half hour's prebreathing of O_2 at the end of the laboratory stage prevented bends even during reconnaissance in 2c.

Under sedentary conditions the elimination of dissolved N_2 from the blood proceeded as shown in Figure 2, according to an overall rate described by the sum of at least two exponentials as checked with a computer program employing Gauss-Newton iteration[7]. When, by the breathing of O_2 at 14.5 psia, the inspired partial pressure of N_2 was abruptly changed from $\simeq$ 580 mm. Hg to nearly zero, the dissolved N_2 (V_g) decreased such that

$$V_g = c_1 e^{-\lambda_1 t} + c_2 e^{-\lambda_2 t} \text{ where}$$
$$c_1 = 1.164 \mu\text{l. of } N_2 \text{ per ml. of blood}$$
$$c_2 = 8.013\ \mu\text{l. of } N_2 \text{ per ml. of blood}$$
$$\lambda_1 = 0.113 \text{ reciprocal hours}$$
$$\lambda_2 = 3.372 \text{ reciprocal hours with t in hours}$$

The half-time of the fast elimination was 12 minutes while that for the slow elimination was nearly 6 hours, meaning V_g was almost entirely determined by c_1 and λ_1 after two hours of O_2 breathing. Therefore, complete reaccumulation in the presence of $\simeq$ 183 mm. Hg of N_2 for 12 hours was fully satisfied for λ_2 but this must have been approximately three-quarters satisfied for λ_1. Altogether, after 12 hours of reaccumulation, the new values of the sum of $c_1' + c_2'$ could have attained 97% of the final level. Since this falls within one standard deviation of the 16 determinations at that time the mean of these can be taken as $c_1' + c_2' \simeq 3.26$ with $c_1' \doteq 0.414$ μl./ml. Further, the values of $\lambda_1 = 0.113$ reciprocal hours and $\lambda_2 = 3.372$ reciprocal hours can be reasonably used as rate constants describing the second elimination of dissolved N_2. This reasoning was used to draw the three curves in Figure 2 which lie within the standard deviations of the measured values.

Only 19 men were subjects of all flights. For these men the correlations between age, body dimensions and bends levels in different flight stages showed that age and physique had generally slight influence on susceptibility to bends. However, the flight stages were highly correlated as to bends levels, which supported the idea that bends, once started, tended to increase in subsequent stages of the same flight*.

DISCUSSION

Laplace's understanding of surface tension recognized[1] that across a curved liquid surface the pressure is greater on the concave side (P_1) than on the convex (P_2) by an amount which depends on the surface tension (γ) and the principal radii of curvature (R_1 and R_2). Work also has to be done against the free surface energy to displace the surface (ABCD) through a distance (δn). The opposing quantities are equal.

$$(P_1 - P_2)\delta n \text{ ABCD} = \gamma \text{ ABCD } \delta n\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

and by cancelling of terms,

*A lengthy correlation matrix will shortly be completed which will include urinary materials that could pertain to objective evaluation of bends symptoms and altogether could furnish a physiological basis for personnel selection.

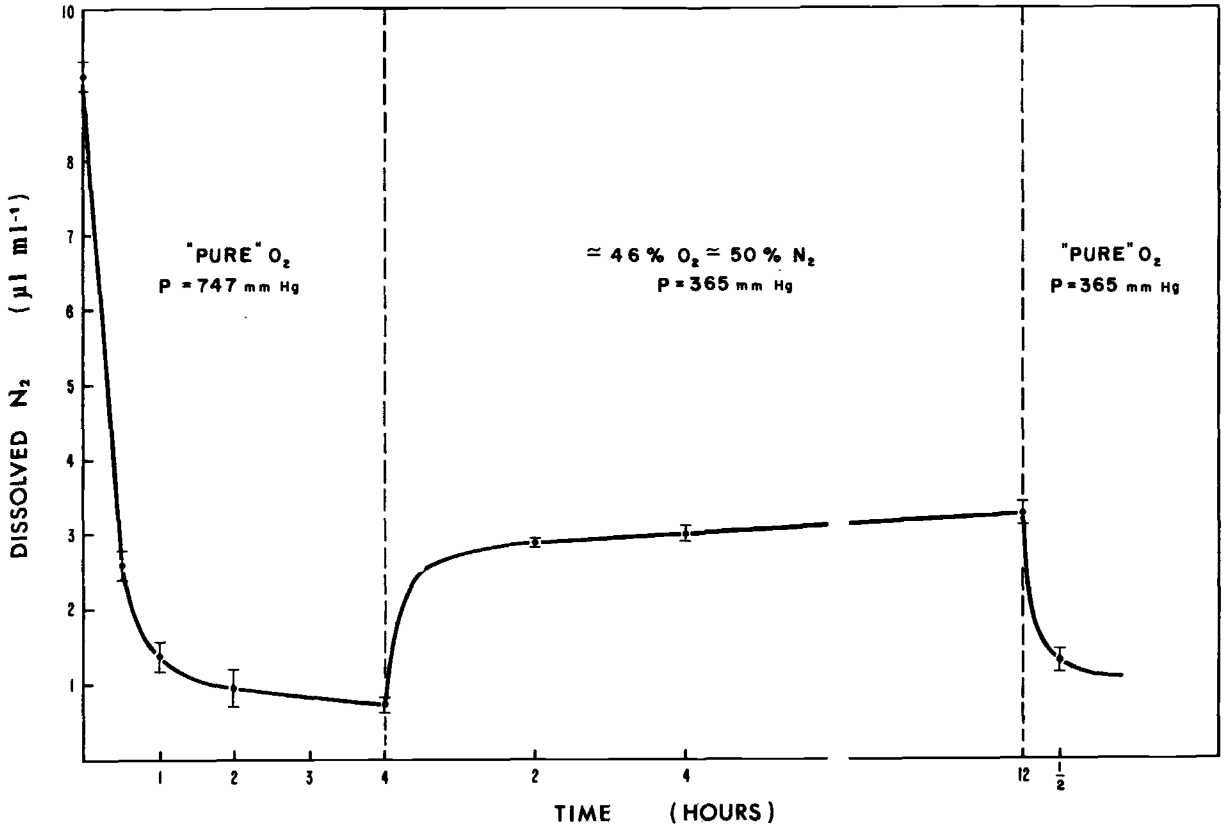

Fig. 2. Elimination and reaccumulation of dissolved N_2 in venous blood of men while breathing different partial pressures of O_2 and N_2.

$$\Delta P = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

from which it follows that for spheres

$$\Delta P = \frac{2\gamma}{r}$$

In 1941, J. Piccard[28] compared the likelihood of birth of gas bubbles in divers and flyers. He started with the idea of a balloon for which the two halves would be pushed apart by a force on the area of a great circle which would be countered by the stresses in the fabric acting on the great circle. Equating of forces gives the same relationship as above. This describes a bubble of a *critical size* lying exactly between the state of collapse by dissolution and the state of growth by coalescence and incorporation of other gas molecules. Seed bubbles were called "gas nuclei" by E. N. Harvey et al.[18] who described principles of formation, growth and shapes of bubbles in animals. However, Piccard had already deduced that the supply of material for formation of a seed bubble depends on the availability of a sufficient number of gas molecules and, in turn, that the probability of creating a seed bubble is much greater when the dissolved gases are dispersed in small instead of large volumes[28].

Although the bends of flyers can be avoided by breathing O_2 with consequent elimination of dissolved N_2 the beneficial effect of "denitrogenation" has not been introduced into a theory dealing with formation of seed bubbles. Before attempting to discuss gas sources for bubbles of a critical size it should be noted that bubbles rarely, if ever, form within living cells[18], even though the chemically active respiratory gases must also be present. Bubbles do form intracellularly in dead or injured cells, but more often these are located extracellularly and continue to grow, especially in vessels draining limbs which have been exercising[19]. Denitrogenation for 30 minutes causes the dissolved N_2 to fall from $10.5(10^{-3})$ ml. per ml. of postcaval blood. Decompression at that time, together with contraction of hind quarters, produces just as many large, mature, visible bubbles as before the denitrogenation. Only after further denitrogenation, when the dissolved N_2 is approximately $1(10^{-3})$ ml. per ml., does bubble formation begin to be prevented[29]. Although blood N_2 was not measured it was clearly shown[15] that 45 minutes of denitrogenation afforded 91 and 82 per cent protection to aviation cadets against *severe* bends and chokes at rest and while exercising, respectively. Early in the course of denitrogenation most of the eliminated N_2 comes from body water, while later this is claimed to come from body fat.[23] This does not exclude other sources. Indeed, new methods support the idea that N_2 and noble gasses are absorbed on proteins. Blood dissolves more N_2 than can be accounted for on the basis of solubility in water and lipid[17]. This is also true of freshly isolated tissues[25].

Suppose, then, that ordinarily a seen bubble entirely consists of N_2. In this case the critical number of molecules is related to that in a mole volume after correction for pressure and temperature of a bubble with a critical volume.

$$^{n}\text{critical} = \frac{N}{22{,}400} \cdot \frac{P_2}{P_1} \cdot \frac{T_1}{T_2}\, ^{v}\text{critical} \ldots\ldots\ldots\ldots (\text{STPD})$$

but the N_2 available per ml. of blood (V_g) furnishes the following:

$$^{n}\text{available} = \frac{N}{22{,}400} V_g \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\text{STPD})$$

whence the ratio of the numbers defines the volume of blood furnishing N_2 to form a bubble of critical radius

$$^{v}\text{blood, critical} = \frac{P_2}{P_1} \frac{T_1}{T_2} \frac{1.33\pi}{V_g} \left(\frac{2\gamma}{P_1 + P_e - P_2}\right)^3$$

P_1 is the pressure in kiloponds ($\equiv$kg./cm.^{2}) at which V_g is stated. P_e varies with exercise. If carried out at five-minute intervals and involving five deep knee bends and five push-ups, $P_e \simeq 0.136$ kp.; at 15-minute intervals, $P_e \simeq 0.063$ kp.; with no exercise $P_e = 0$ kp.[16] P_2 is the pressure in kp. following decompression. The surface tension of blood is approximately 58 dynes $\times$ cm.[4] and, therefore, $2\gamma = 116(10^{-6})$ kg./cm. Numerically, the above equation becomes for these conditions

$$^{v}\text{blood, critical} = \frac{3.57\ P_2}{V_g} \left(\frac{0.000116}{1.033 + P_e - P_2}\right)^3$$

Shown by the abscissa of Figure 3 are calculated volumes of blood required for formation of seed bubbles during various stages of the present flights (filled circles) for which the average volume of N_2 per ml. of blood was calculated with the rate constants λ_1 and λ_2 together with c_1 and c_2 values (Figure 2). Also

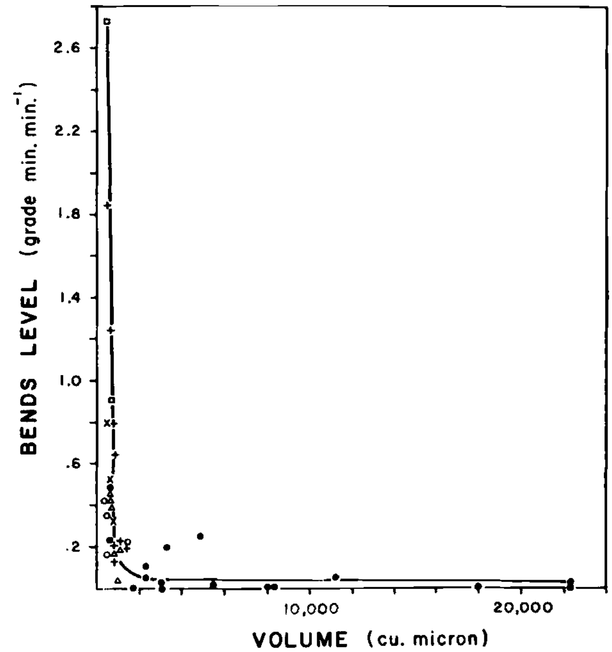

Fig. 3. Relationship between level of bends and the volume of blood required to form a N_2 seed bubble.

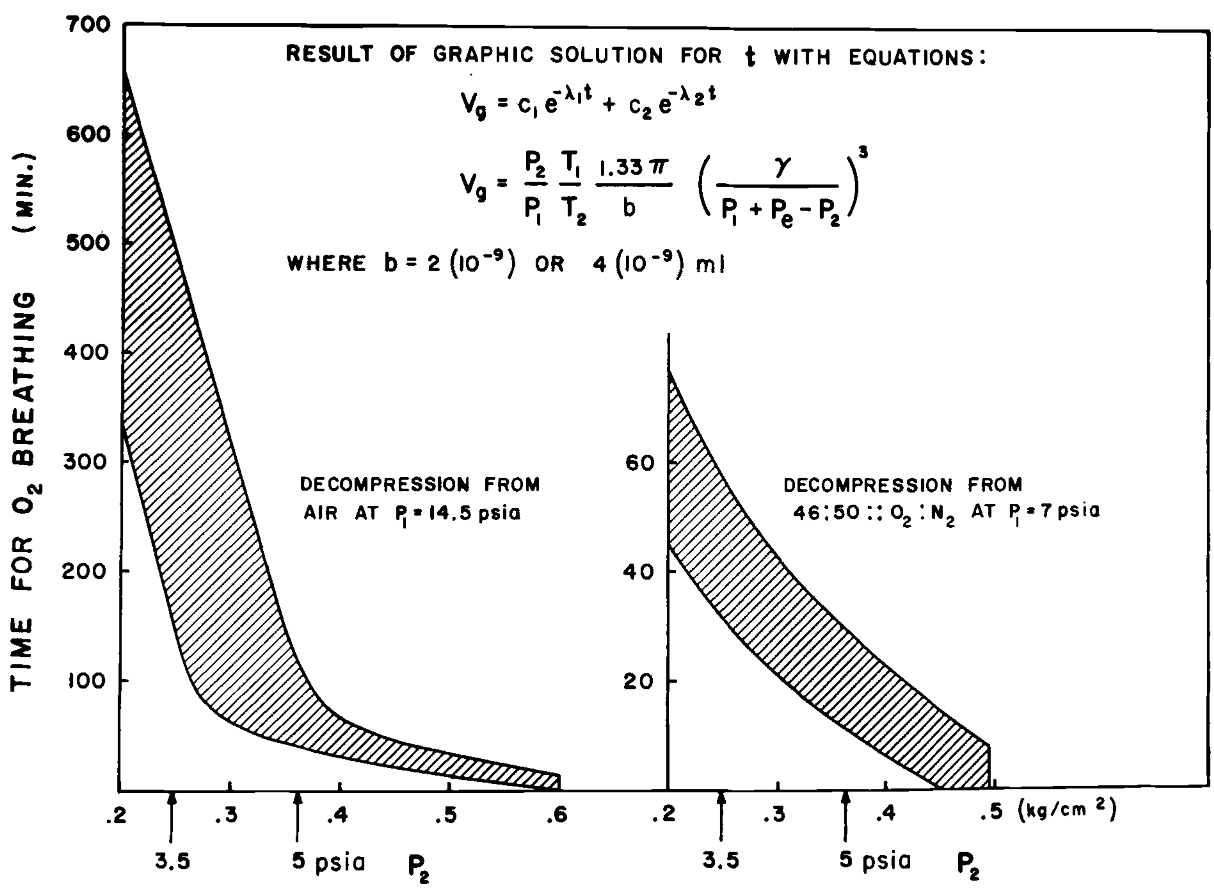

Fig. 4. Time required for O_2 breathing before decompression to indicate pressure and then exercising.

shown are data calculated similarly from original unpublished records taken during Balke's journey to Mt. Evans (triangles) and from the reports by Marbarger et al[24] following several hours at moderately low pressures while breathing different mixtures (circles), by Damato et al[6] on abrupt decompressions and following 12 to 24 hours exposure to 50:50::O_2:N_2 at 7.5 psia, and by Gray and Masland,[16] who observed large numbers of men at rest and while exercising at a number of low pressures (crosses). Except for one of the cited experiments[24] it was assumed that denitrogenation started from a level directly related to the ambient partial pressure of N_2. The ordinate of Figure 3 shows the average intensity:duration of bends pains. This was calculated from records on each subject except for two reports[6,16] for which the total incidence of mild bends (taken as grade 1.5) was considered, together with the total incidence of severe bends (taken as grade 3).

The visually-fitted curve in Figure 3 suggests a hyperbola for which the level of bends takes the place of P in PV relationships for an ideal gas under pressure at a constant temperature. Although there is some scatter of the data, below a certain range in volume the intensity:duration of bends is many times greater than above this range. At volumes above 2,000 cu. microns, the average intensity:duration of bends is only 0.0462, showing that mild bends in one out of 22 men could be caused by phenomena other than diffusion of N_2. This is not likely to involve cavitation for reasons given by others.[18] Perhaps it is due to delayed growth of previously acquired bubbles, oft-called "quiet" bubbles. It also could be caused by diffusion of other gases in which case the hypothesis is void to this small extent. There might indeed be no physical basis for bends when the N_2 needed to form a seed bubble is dispersed in volumes larger than 2,000 to 4,000 cu. microns.

Accepting the above concepts on critical volumes allows rewriting of the preceding equation in terms of the pressures at which the level of dissolved N_2 would scarcely suffice to cause bends. Since the elimination of dissolved N_2 is a function of time, it becomes possible to estimate the time required for breathing of O_2 prior to going to a lower pressure (P_2) and then engaging in exercise (P_e). This is shown by the two sets of curves in Figure 4 for the condition involving bouts of exercise at 5-minute intervals. Thus an aerospace mission in a "pure" O_2 environment would require at least 43 minutes, and preferably 120 minutes, of breathing O_2 at 14.5 psia before decompression to 5.0 psia. It would be unwise to decompress to 3.5 psia until passage of an additional 120 to 375 minutes. Following this it would be equally safe to return to pure O_2 at a pressure of 5.0 psia or to change the interior gases to 46:50::O_2:N_2 at a total pressure of 7.0 psia. Dissolved N_2 reaccumulates in the latter environment. Therefore, if this total pressure is again decreased it would take 33 to possibly 57 minutes of O_2 breathing before it would be safe to decompress to 3.5 psia. The range in estimated times is caused by present uncertainty as to whether the N_2 needed to create a seed bubble is dissolved in either $2(10^{-9})$ or $4(10^{-9})$ ml. of blood. For safety's sake select the longer times or else insist on pressure suits that operate successfully at 5.0 instead of 3.5 psia.

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