1959

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Wallace Marven Landholm
University of Nebraska Medical Center

Recommended Citation

Landholm, Wallace Marven, "Problems of dysbarism" (1959). *MD Theses*. 2406.
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PROBLEMS OF DYSBARISM

Wallace Marven Landholm

Submitted in Partial Fullfillment for the
Degree of Doctor of Medicine

College of Medicine, University of Nebraska

January 31, 1959

Omaha, Nebraska

Table of Contents

Problems of Dysbarism

Introduction

In this "Space Age" man is more than ever looking toward the sky with the desire to explore and to use to better advantage that infinite space beyond the earth. Man is constantly showing his desire to explore further and gain more knowledge of the space above him as is now evidenced by the sending of balloons, airplanes, rockets and satellites higher and higher into the air. He is taking advantage of the space above him as is shown by the great increase in both military and civilian air transportation. Man has now found that if he flies above 35,000 feet, he can utilize the "jet streams" to go faster and farther with less fuel. These high altitudes, however, present a somewhat different environment than is found near the earth's surface.

In this age of greatly increasing air travel, it behooves physicians, and especially a prospective Air Force medical officer as I am myself, to become aware of some of the problems which this new environment imposes upon its inhabitants. The next half century or even the next decade will in all probability, take the average traveler to altitudes at which the problem of dysbarism must be guarded against. Since a modern army must be quickly mobile, much of the transportation of men and equipment is by air. For this reason, almost any physician in the service should be cognisant of the problems encountered at high altitudes, in order to best serve his men.

Many patients under medical care will consult their physician as to the advisability of their traveling by air. If the physician is aware of some of the facets present at high altitude, he will be better able to give the proper advice. Although the scope of aviation medicine is too broad to present at this time, the reader may gain some general idea of problems at high altitude other than dysbarism.

The higher you ascend from the earth's surface, the fewer the number of molecules of air present per unit of space. This also causes a reduction in the barometric pressure and is one of the major problems which this high altitude environment imposes on its occupants. When one refers to the symptom complex developing due to exposure at high altitudes, dysbarism is the preferred term.

Although you cannot ignore the fact that there is less oxygen the higher you ascend, dysbarism must further be defined as including all the physiological effects due to reduction in barometric pressure, independent of any effects of hypoxia.

I regret that the facilities for personal experimentation are not available to me at this time. Therefore, I have mainly by examination of the literature, attempted to present some of the problems, experiments, facts and solutions which the study of dysbarism has revealed.

History

The physiological effects of changes in barometric pressure have been a problem to man ever since his needs and his inquisitiveness drove him deep into the oceans and high into the air. It increased as greater depths and ever increasing heights were reached. Until, at the present time, with fast high altitude travel and the beginnings of the conquest of space, it has become necessary to know what the effects of changes in barometric pressure are, and how they can best be overcome.

Increased pressure, and the symptoms arising in man upon release of these pressures, presented a need for the understanding of dysbarism. The invention of the diving bell by Sturmius in the beginning of the sixteenth century was the beginning of the use of compressed air as an atmosphere in which men work.(52) Then in 1839, M. Trigier used the principle employed in caissons to sink a shaft through quicksand to reach a large bed of coal. The first fairly careful and complete observations made of the results of compression and decompression were recorded by M.M. Pol and Watelle, in 1847, from observations made of miners during the excavation at Avaleresse-la-Neville at Lourches. Some of the symptoms of decompression sickness are similar to those of dysbarism. An example of their observations is as follows: A man commenced work at 4.154 atmospheres. This man went into compressed air only once and came out too rapidly. Some minutes after coming out he had the appearance of a cadaver; his face was livid, icy cold, eyes dull, pupils dilated, and he had troubled respiration. On listening to the heart, only a vague agitation was heard, the pulse was imperceptible, intelligence was abolished and micturition involuntary. After hot baths, blankets, and frictions, in half an hour, the pulse began to become perceptible. A little heat returned to the trunk, and he began to talk, but incoherently. During the night, when the temperature had returned to normal, severe pains came on in the muscles, aching pain in the head, with blindness and deafness, and the pulse was poor. He was completely recovered by the following morning, but feeble sight and enormously dilated pupils remained.(52) Later, attempts were made to use variations in barometric pressure therapeutically, arising from the observation of effects of increased pressure on asthmatics and those suffering from other conditions upon whom increased pressure seemed to have palliative effects. (2)

At about the same time, the effects of varying barometric pressures were being described by the first balloonists. On October 15, 1783, Pilatre de Rozier made man's first ascent in a smoke filled balloon. The same year Charles built the first hydrogen balloon.(14) Because of these events, interest in ballooning became widespread and in 1794, the French began using balloons for observation, during the battle of Fleurus. In 1862 Glaisher and Coxwell ascended to an altitude of approximately 29,000 feet, and Glaisher's published account of this, and other flights, interested Paul Bert in the effects of increased and decreased barometric pressure.(2) Actually, Paul Bert became the first flight surgeon, and in 1878, published La Pression Barometric. Part of Bert's interest stemmed from the disastrous ballon flight to 28,820 feet made by Tissandier, Croce, and Sivel, from which only Tissandier survived. The other two died from the effects of the altitude reached by the balloon. In his book, Bert showed for the first time that the symptoms following rapid decompression were due to the liberation of a gas in the body and that this gas was chiefly nitrogen. Earlier observations had already been made along these lines, for instance in 1670, Robert Boyle reported seeing a bubble in the eye of a snake exposed to a high vacuum, and in 1857, Hoppe stated that animals rapidly exposed to a partial vacuum of 50 mm of mercury pressure or less had gas bubbles formed in their blood in the same manner as those occurring on sudden decompression from pressures higher than two atmospheres.(3)

As far as actual successful flight by man is concerned, the flight at Kitty Hawk, North Carolina, by the Wright brothers in 1903 might be said to be the beginning. Earlier work leading up to that day was done by da Vinci, Sir George Cayley, Le Bris, Otto Lilienthal, and Octave Chanute, among others. The first world war caused an intense interest in aviation and concurrant with this development was an interest in aviation medicine. On February 2, 1912, the war department of the United States published the first list of physical requirements for pilots. In 1914 a memorandum was sent to the Chief Signal Officer of the Army describing the physical examinations to be used for applicants for transfer into the "Aviation Section". After a month or six weeks the examining officer returned to announce that the standards were so high no applicant had been able to pass the examinations and requested that they be lowered so the Aviation Section could obtain personnel! At the end of the first year of World War I an analysis of Great Britains Casualty List showed that of every one hundred fliers killed, two had met death at the hands of the enemy, eight through some defect in their planes, and ninety because of some individual deficiency, either physical or psychological. Of the ninety deaths, sixty were found to be due to some physical defect. Partly due to the effect of the publication of these figures, a Medical Research Board was established in the United States in 1917 consisting of four officers and one civilian.(58) Then in 1918, the Air Service Medical Research Laboratory was established.

In 1926 the Bureau of Air Commerce was created with a medical section under Col. Louis H. Bauer. Major David Myers of the Army Medical Corps did the original research on the physiology of blind flight, which is the basis of all present blind flying equipment.(57) Then in 1927, Lindbergh made his transoceanic flight and the country became air minded almost overnight.

In 1929, the Aero Medical Association of the United States was organized because of the need for civilian flight surgeons created by establishment of a rule requiring all airline pilots to take a medical examination. It was not until 1935 and 1936, however, that the larger airlines set up their own official medical departments.(35)

In 1931, Auguste Picard was responsible for the beginnings of the large manned balloon and sealed cabin for stratospheric flight, which subsequently became a new high altitude research tool.(42)

In 1935, Anderson and Stevens ascended to between thirteen and fourteen miles above sea level via balloon. And on August 18th, 1957, Major David Simons ascended to 100,000 feet (more than 19 miles) above the earth.(50) The present worlds altitude record is held by Captain Iven Kincheloe, who flew a rocket plane to 126,200 feet.(11)

Further conquest of high altitudes and space travel will depend on the continued solution of the problems met by man in these regions. One of the major problems confronting man as he goes higher and higher is the interesting problem of dysbarism.

Definitions and Etiology

"Dysbarism includes all the physiological effects of reduction in barometric pressure, independent of any effects of hypoxia."(18) A decrease in barometric pressure has undesirable effects on the body in addition to giving rise to oxygen want. The symptoms which have been known under the name of decompression sickness, or bends, occur even though the oxygen saturation of the arterial blood remains normal by the inhalation of oxygen. The effects are mainly due to: 1) The expansion of free gases in certain body cavities from which the gas can not readily escape. This expansion puts undue pressure on the walls of the cavity with resultant stretching and pain, and occasionally some pathologic change may be brought about. 2) Evolved gases, principally nitrogen, which escape from solution into the blood and tissue fluids and may give rise to bends, chokes, and neurological symptoms. This disturbance, resulting from decompression from one atmosphere to less than one atmosphere is known as aeroembolism. It is similar to that experienced by deep-sea divers and others who work under greater than atmospheric pressures, and who experience bends on decompression to sea-level pressures.(35) Although deep sea divers call this phenomenon decompression sickness, in the high altitude form of this disease one has to cope with slightly different variables, i.e., lower partial pressures of gasses and, in general, lower temperatures. To avoid any confusion, the high altitude phenomenon resulting from reduction in barometric pressure is thus termed dysbarism.(18)

A review of certain physical laws would help to understand the etiology of decompression sickness. When an airplane ascends to a higher altitude, in general, the volume of any free gas within the body increases in accordance with BOYLE'S law, i.e., the volume of a gas is inversely proportional to the pressure being exerted on it. However, gases within the body tend to expand more than BOYLE'S law demands when the barometric pressure is reduced. This is explained by the fact that 1) at body temperature, the gas remains saturated with water vapor, and 2) the tensions of oxygen and carbon dioxide decrease at altitude by a slower rate than the barometric pressure.(35)

It would at this time, be wise to describe a few of the concepts with which we will be dealing. The structure of a gas can be described by using the concept that gas molecules are comparatively far apart, and move about unceasingly throughout the entire space in which they are confined. The gas particles suffer countless collisions between themselves and the walls of any container, during the course of their movement. Any sudden removal of the container's walls would result in a swift dissipation of the gas into the surrounding environment. The collisions occurring between the particles are assumed to be perfectly elastic. In an elastic collision, the sum of the kinetic energies of the two colliding particles remains unchanged. An ideal gas is defined as a gas which involves elastic collisions as the only microphysical process.

This concept of a gas readily accounts for an outstanding property of a gas, its compressibility and expandibility. Four variables which determine the condition of a confined body of gas are as follows: 1) pressure, 2) volume, 3) temperature, and 4) density.

Pressure being exerted by a confined body of gas upon the walls of the container is produced by the continual bombardment of the walls by the gas particles. Because pressure has the physical dimension of force per unit area (gm/cm^2), it can be measured as illustrated in Fig. 1.

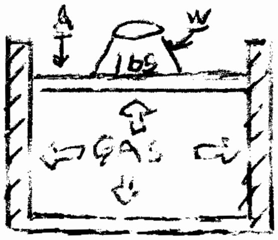


Figure 1

Gas can be confined within a closed cylinder, having a tight fitting piston and a weight may be placed there. The enclosed gas will be compressed under the weight until the pressure of the gas has increased to the point of equilibrium. If you disregard the pistons weight and friction, the pressure of the gas then equals W/A, A being the area of the piston. This value of the pressure is then the same throughout the gas. This is sometimes known as PASCAL'S principle and may be stated as follows(22): Whenever the pressure of a confined gas is increased or diminished at any point, this change in pressure is transmitted equally throughout the entire gas.(47) The measurement of gas pressure is done in a more practical manner using two main methods. One involves gas pushing mercury up into a tube containing a vacuum and the pressure is then read in terms of mm of mercury. The other involves a sensitive diaphragm which pushes in and out against a carefully calibrated spring. The distance this diaphragm is moved, due to a pressure change, is recorded by a pointer, which in turn indicates the pressure on a calibrated scale.

The volume of a confined body of gas is the amount of space being occupied by the gas. The volume of the gas remains constant if the container is assumed to be perfectly rigid.

Temperature measures the energy content of the gas. The energy content is a measure of the sum of the kinetic energies of the individual gas molecules at any particular instant. When the temperature increases, the mean kinetic energy of the gas particles increases. The measurement of temperature is done with thermometers. Temperature for scientific purposes is preferably expressed in units of Kelvin. This unit of Kelvin temperature scale is defined as one-hundredth of the temperature difference between melting ice and boiling water, at a pressure of 1,013 millibars.(22)

Density determines the number of molecules which hit any area each second,(15) and is the fourth variable which governs the condition of a confined body of gas.(22) The density of a substance is defined as the ratio of the mass of a sample of the gas to its volume, i.e., d equals m/v where d is the density of the substance, m the mass of the sample, and v its volume. The densities of solids and liquids vary only slightly with changes of temperature and pressure, while the densities of gases vary greatly with changes of temperature and pressure. The density of water is 1 gm/cm^3, while the density of air at 0^oC. and atmospheric pressure is 0.001293 gm/cm.(47)

In a thorough study of dysbarism, an understanding of the gas laws is important. The four principal gas laws were named after the men who formulated them. The LAW OF DALTON is concerned with the pressure of mixtures of gases. Assuming that two or mor different gases are admitted to a confinėd space, the molecular motion causes an individual gas to penetrate the entire available volume, and by this process of diffusion, the final mixture of gases becomes homogeneous throughout. Each of the constituent gases will have expanded into the entire space of the container after completion of the diffusion process, just as though the other gases were absent. Then if by some procedure, all the gases except one were removed, the remaining gas would exert its pressure on the walls of the container and is called the "partial pressure" of that particular gas. If the same procedure was in turn repeated for each gas, and the partial pressures of all gases were measured, we would notice that the sum of all the partial pressures would be equal to the pressure of the gas mixture. We then define the partial pressure of a gas in a mixture as that pressure the gas would exert if it were allowed to occupy the entire space alone. It becomes evident that DALTON'S law must be dealt with in all places where mixtures of gases are present.

The LAW OF BOYLE deals with the pressure and volume of a body of gas under the condition of a constant temperature. This law states that the pressure and volume of a body of gas are inversely proportional. Therefore expanding a gas by twice its original volume cuts the pressure in half and compressing a gas into half its volume doubles its pressure, with the provision that the emperature of the gas is allowed to remain constant.(22) Therefore if p is denoted as gas pressure and v as its volume we have v_1/v equals p/p_1,(47) or if you use a graphic representation of the law, the graph is a hyperbola as shown in Figure 2.

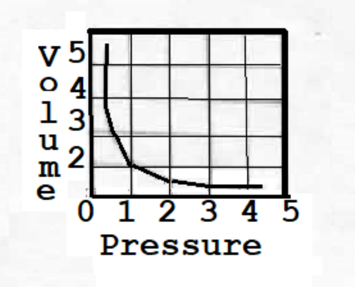


Figure 2

If the temperature remains unchanged, BOYLE'S LAW permits calculations of the changes in volume of trapped bodies of gases of bubbles, as soon as any changes of pressure are known, and vice versa. Since the density of a gas varies inversely with its volume, a decrease in volume means an increase in density. Thus when the pressure in a mass of gas is increased, its density is also increased in the same ratio. Thus BOYLE'S LAW may also be written as p/p_1 equals d/d_1 where d is the density of the gas at pressure p and d_1 is the density of the gas at pressure p_1.

The LAW OF CHARLES-GAY LUSSAC, when combined with BOYLE'S law, is known as the general gas law. This law includes temperature in the relationship between pressure and volume of an enclosed body of gas. The temperature can be included in two different steps: 1) by studying the pressure changes resulting from temperature changes while the volume of the gas remains the same; 2) by studying the volume changes resulting from changes in temperature, while the pressure remains the same. These separate studies reveal that both volume and pressure increase in proportion to an increase in temperature. In either case, the rate of increase is dependent upon a known coefficient. The two involved are called the pressure coefficient and the volume expansion coefficient, The two coefficients are equal, however, with a numerical value of 0.00367 $/^{\circ}K$. This makes it unnecessary to distinguish between the two coefficients and permits a simple expression of the general relationship between the three variables of a state of a gas. It is known as the general gas law and can be expressed as follows: p.v equals R_n.T where T is measured in degrees Kelvin, R_n being a constant. This general gas law is very convenient in determing the pressure, volume or temperature when two of the three factors are known.

HENRY'S LAW is related to the solubility of gases in liquids. If the surface of a liquid becomes the wall of a confined space filled with a gas (or a gas mixture), a certain amount of the gas will enter the liquid and go into solution. Gas molecules will leave the liquid and re-enter the gas at the same time. When the number of particles leaving and entering the liquid per unit of time are equal, a state of equilibrium will have been reached. The number of gas particles dissolved per unit volume of the liquid remains constant under these conditions. For each particular gas present above the liquid, the amount dissolved remains constant. The amount of gas dissolved also depends on the nature of the liquid, the temperature, and the partial pressure of the gas under consideration.(22) In general, the solubility of gases in liquids decreases with an increase in temperature. HENRY'S LAW in particular has to do with the relationship of the amount of gas in solution per cm^3 of the liquid and the partial pressure of the gas above the liquid.

The quantity of gas dissolved in 1 cm^3 of the liquid is thus proportional to the partial pressure of the gas.(55) This is true only if all gases do not react chemically with the liquid. Since pressure and volume of an ideal gas are inversely proportional at a constant temperature, HENRY'S LAW further states that the volume of gas lost by solution in a constant amount of liquid remains the same regardless of the pressure applied. This volume in the solution is called the absorption coefficient. The solubility of gases in liquids is measured in the volumes of gas absorbed per cm^3 of the liquid at a specified temperature. Table 1 below will give the absorption coefficients for some of the more important gases involved in the study of dysbarism.

Table 1

Gas	Volume of gas absorbed in 1 cm^3 of water at 20°C	cm^3 at 0°C
Hydrogen	0.0182	0.0215
Oxygen	0.0310	0.0489
Nitrogen	0.0157	0.0232
Helium	0.0085	0.0096
Carbon dioxide	0.878	1.713

The fact that the absorption coefficient for Helium is about half that of nitrogen would tend to support the proponents who feel that helium should be combined with oxygen instead of using nitrogen in a high altitude artificial atmosphere. Helium would not be as prone to cause symptoms of the bends, should there be a sudden decompression, because less will be dissolved in the body fluids. The LAW OF GRAHAM is important as it describes the relationship between density and the diffusion velocity of a gas. It states that the velocity with which a gas passes through a porous wall or membrane is inversely proportional to the square root of the density of the gas.(22) This would mean that helium, for example, would pass through a porous boundry at a rate of 2.57 times as great a rate as nitrogen, since the density of nitrogen is over 7 times as great as that of helium.(25) This would also tend to support the replacement of helium for nitrogen in an artificial atmosphere to prevent the bends. Nevertheless, the greater mobility you might expect from helium is not realized because the gas exchange rate in the body is mostly determined by the rate of tissue perfusion by the blood.(4) There are additional complications which will be discussed at a later time.

If you have ever noticed the bubbles which form in a bottle of soda pop when the cap is removed, you have noticed a phenomenon of HENRY'S LAW. This is due to a gas saturated liquid in which the partial pressure of the overlying gas is decreased suddenly. This results in an over saturated solution in which bubble formation sets in explosively in an attempt to follow HENRY'S LAW.(55) This is the same phenomenon that happens when the human body is decompressed at a rate which is very rapid and the body can't equalize the partial pressures of the atmospheric gases with those dissolved in the body fluids. When the tissue fluids become oversaturated, bubble formation may occur and the problem of bends may occur.(22)

With a basic understanding of how gases act under certain conditions, it is not difficult to understand the etiology of various forms of dysbarism. For example, under decreased pressure, an expansion of the existing gases within the body cavities occur. Although it is true gases tend to expand to a greater degree than can be explained simply on the basis of BOYLE'S LAW, with a basic knowledge, it is easier to understand the more complex problems. This exaggerated expansion of gas is because the gas remains saturated with water vapor at body temperature, and because the tensions of oxygen and carbon dioxide decrease at altitude slower than the barometric pressure. A common example of this exaggerated gaseous expansion is within the bowel and it often causes abdominal pain.(18) As Table 2 below indicates, the expansion of gases is quite significant.

Table 2

The Comparative Volumes of the G.I. Gases at Various Altitudes

Altitude in feet	Relative gas volume
0	1.0
5,000	1.2
10,000	1.5
15,000	1.9
20,000	2.4
25,000	3.0
30,000	4.0
35,000	5.4
40,000	7.6

This should also hold true for gases trapped for various reasons within sinus cavities, in teeth with fillings, in the middle ear, in the pulmonary system or at any other location in the body where the gas cannot readily escape.(3)

The average adult body contains about one liter of nitrogen gas in dissolved form at sea level. According to HENRY'S LAW, smaller amounts of this gas can be retained in solution as the barometric pressure is decreased. Nitrogen is evolved from solution in the form of gaseous bubbles, which, depending upon the location and quantity of the bubbles, produce symptoms of dysbarism. The symptoms of bends are produced by bubbles forming within the interstitial and connective tissue, about joints, bones, and muscles. The symptoms of the chokes is caused by the collection of many such bubbles within the blood vessels in the pulmonary circulation. There are also neurological manifestations which will be described at a later time. The incidence of dysbarism increases with activity, duration of exposure to altitude, rate of ascent, and cold, and decreases with denitrogenation. Age has so far been listed as affecting individual susceptibility. The individual susceptibility varies very much from person to person and within each individual from time to time. Previously healed injuries to bones and joints, within the limits found in personnel on average flying status and physical fitness, do not appear to influence susceptibility. Exercise increases the incidence of dysbarism at a certain altitude, and also lowers the threshold altitude where bends occur. Usually bends doesn't occur until thirty thousand feet in altitude is reached but symptoms may occur before twenty two thousand feet if strenuous exercise occurs.(18)

There are other physiological effects which can occur at high altitudes and will be mentioned in a later section. Although they are less common, they are very important to any individual who suffers from them. Both civilian and military sources of high altitude transportation, have recognized the great importance of dysbarism and have gone to great lengths to prevent it. Regardless of how careful they are, on occasion some individuals at high altitude are exposed to the effects of a rapid reduction in barometric pressure. This fact and the possibility of future space travel has greatly increased recent research on the important problem of dysbarism.

Signs and Symptoms

With experimentation and an increasing understanding of the varied signs and symptoms of dysbarism, man is relentlessly pushing back the high altitude frontier, as this hostile environment becomes safer and safer for man. There are a variety of presenting symptoms, but the five most common painful reactions of dysbarism are aeroembolism or bends 13%, aerotitis 7.86%, abdominal distresses 4%, sinus pain 1.17%, and aerodontalgia. The chokes, vasomotor instability, hypoxia, visual disturbances and hyperventilation all add up to less than 1%.

These statistics are the results of a decompression reaction study on 62,060 trainees from 1943-1945. Although these percentages seem low, when you stop to consider that 13% of the individuals who are exposed to altitudes at which bends occur will suffer from this disorder, then the problem assumes much greater magnitude.(18) Not only will there be individuals who are suffering from the bends, a certain percentage of the remaining individuals will be stricken with other symptoms of dysbarism. Much of the civilian and military aircraft are not equipped with pressurized cabins, and sometimes weather and terrain forces these aircraft to be quickly subjected to depressurization and the effects of low atmospheric pressure.(44)

Aeroembolism

"Bends" are the most frequent of the symptoms and are characterized by deep pain in the extremities. The pain is often migratory and is hard to localize. The onset of pain may be sudden or gradual. The larger joints, especially the shoulder and knee are most often affected, with the smaller joints like the hands, ankles and wrists also often being involved.(38) This pain sometimes begins mildly, but many times becomes deep, gnawing, and so severe as to be unbearable, causing collapse. Sometimes mild symptoms will disappear after a few minutes to an hour. Although the mechanism which causes the pain produced by the evolved nitrogen bubbles is not definitely known, it was originally attributed to the occlusion of blood vessels by the bubbles. It is now thought by many to be caused by a distortion of nerve endings in the surrounding tissue. I believe that the occlusion of an end artery could result in ischemic pain as in angina or myocardial infarction. Also the theory that the distortion of nerve endings in tissue causes pain, seems sound. It thus seems entirely possible that both mechanisms may be instrumental in the etiology of the pain.(35)

If one would have the subjects breathe pure oxygen before going to these heights, the oxygen might replace the nitrogen in the body and rid the patient of most of these nitrogen bubbles that cause pain. An interesting experiment which shows the location of the symptoms and the length of time before onset in fifteen healthy male subjects is well presented in the Table 3.(32) The subjects performed a mild amount of exercise and thus weren't at complete rest.

Table 3

TIME IN MINUTES DURING A THIRTY MINUTE PERIOD AT 38,000 FEET BEFORE BENDS DEVELOPED AND LOCATION OF PAIN IN EACH SUBJECT FOR EACH OF THREE EXPERIMENTS

Subject	Without Denitrogenation				2 Hours at 18,000 Feet 100% Oxygen	
	Control 1		Control 2			
	Time	Location	Time	Location	Time	Location
R.F.A.	22	R. knee	12	L. knee	No bends	—
R.B.B.	1	R. knee	5	R. knee	25	R. knee
J.B.B.	11	R. knee	29	R-L knee Burning chest	No bends	—
J.W.B.B.	21	R. wrist	15	R. wrist	15	R. ankle and wrist
R.A.B.B.	22	L. knee	16	R. knee	No bends	—
W.C.C.	27	L. ankle R. knee	19	R. knee	No bends	—
G.G.G.	15	L. knee	17	L. shoulder	26	R. knee
J.H.H.	19	R. hip	15	R. knee	No bends	—
E.J.J.	18	L-R knee	13	L. knee	19	L. knee
D.K.K.	22	L-R ankle	25	R. knee	18	R. knee
R.L.L.	20	R. knee	19	L. knee	29	R. knee
L.L.L.	13	R. knee	18	L. knee	26	L-R knee
E.S.S.	19	L. knee	21	R. knee	No bends	—
L.T.T.	22	L-R knee	9	R. ankle	14	R. knee & ankle
J.T.T.	6	R. knee	7	L. knee	9	R. knee

Other controls were run which showed similar results. This seems to bear out the fact of the greater incidence of bends in the larger joints.(32)

There have been many experiments and reports done to record the physiologic effects of reduction in barometric pressures. I have attempted to present only the more significant and representative of these in as concise a manner as the situation warrants.

As long ago as 1934, a series of experiments were done to ascertain if nitrogen bubbles were formed in the blood during ascent to high altitudes in the same way that they occur during the rise to the surface in deep sea diving. Scientists exposed animals to varied decreased atmospheric pressures in the altitude chamber and then did a postmortem examination of the cardiovascular system at sea level pressure. Although the animals were fairly rapidly taken to as high an altitude as they could survive while breathing pure oxygen, there was no evidence of bubbles in the blood. Then it was decided that the negative results could have been due to returning the animals to sea level pressure before the autopsy was done. This could drive any bubbles that had formed back into the blood. Therefore, they decided to perform the autopsy in the high altitude chamber, at altitude. To accomplish this, they placed an observer in the altitude chamber with the experimental animals and he was then also subjected to the same rate of climb and decrease in barometric pressure. A constant rate of climb of 1,000 feet per minute was used and at various altitudes the animals were killed and postmortem examinations done. Their plan was to make the first trial to 20,000 feet simulated altitude and to increase each trial by 1,000 feet until nitrogen bubbles were found or until the limit of human tolerance had been reached. The first sixteen experiments were entirely negative, but during the postmortem examination on the 17th trial, at a simulated altitude of 37,000 feet, the operator noticed that his fingers were becoming stiff and his finger joints painful and sore. Stopping for a moment to massage his fingers, in an attempt to limber them up, he discovered a row of small, round, freely movable gas bubbles filling the flexor tendon sheath of his left index finger. These bubbles could be plainly felt by putting an opposing finger at the base of this tendon sheath and passing it toward the tip of the affected finger. They were easily felt as they then squirted back toward the base of the finger.

Although this discovery had furnished no definite proof that they were nitrogen bubbles, or that there were any nitrogen bubbles present in the blood stream, this was enough evidence to encourage further experimental effort which otherwise would shortly have been discontinued. Since they had not been able to find any evidence of nitrogen bubbles in the experimental animals up to this point, they decided to greatly increase the rate of ascent. In order to do this without increasing the rate of ascent of the observer, they placed the animals in a small separate sealed chamber and then placed this chamber inside the altitude chamber. The small chamber with the animals was kept sealed at sea level pressure. Then the observer in the altitude chamber was taken to the desired simulated altitude at the usual rate of ascent. Next a valve was opened in the animal chamber and could be taken to 40,000 feet altitude pressure in as short a time as 40 seconds. Even with this change in rate of ascent, there were no bubbles to be found, anywhere in the experimental animals. During these experiments the observer was getting into greater and greater difficulties of his own which simulated attacks identical with those which are described as being pathognomonic of decompression sickness. This led to the further belief that nitrogen bubbles were present in the blood of the observer in spite of the fact that there had been no evidence from the experimental animals to support this.

Although the rabbits had been subjected to more severe conditions, in the form of more rapid rates of ascent, there had been no evidence of symptoms or bubbles in their blood. Since the observer had had severe attacks which were typical of the bends, they finally concluded that either the difference in circulatory and respiratory rates or the different body mass or both together explained the different results. A rabbit's heart rate and respiratory rate are much faster than in man. The circulation time would be much less in a rabbit due to both increased rate of flow and a shorter distance to travel. This would enable a rabbit to rid its body of nitrogen much faster than man. Also the total body mass and thus the amount of dissolved nitrogen is much less in rabbits than man. To enable them to prove this theory, they obtained a number of goats, which are still not as large as man, and subjected the goats to the same experimental procedures. In these larger animals, nitrogen bubbles were then easily demonstrated, not only in their blood, but in almost all the tissues of their bodies.(3)

After the early investigations had definitely es-tablished the presence of bubbles in the blood at a high altitude, they conducted a group of studies to investi-gate other phases of dysbarism. These investigators, having a sound background in the laws of physics, knew that a fluid can be caused to boil by either increasing its temperature, or by decreasing its superimposed vapor pressure, which raises the vapor pressure of the fluid higher than the superimposed pressure. Theoretically, the same events should occur in the body fluids at their normal temperature of 98.6° F. if the atmospheric pres-sure is decreased to the vapor tension of the body fluids. This occurs at a simulated altitude of 63,000 feet and corresponds to 47 mm of mercury absolute pressure.

Harry G. Armstrong, in 1936, began investigating the possibility of this phenomenon actually occurring. They had previously learned that animals could not be kept alive at simulated altitudes of over 45,000 feet for over a few minutes, partly because of the lack of sufficient oxygen.

They were compelled to thus slowly decrease the pressure on the animals to a simulated altitude of 40,000 feet and then very rapidly ascend to an altitude above 63,000 feet which was maintained until the animal died. In the typical results obtained by this procedure it was found that the body fluids actually did boil and the amount of water which was lost during this process was determined. For example, at 70,000 feet, if the animal survived for about three minutes, the amount of water lost from the body was three pounds, when the original weight of the animal was 126 pounds. This loss in body weight is about 3/4 of 1% per minute, which is phenomenal. Since the altitude chamber temperature was only slightly below the body temperature, the water vaporlost from the body didn't condense and thus wasn't visible as steam. However, the saliva about the mouth and the serum about the incision for the tracheal canulae bubbled rapidly when about 63,000 feet altitude was reached.

A further study which is quite intriguing was designed to directly observe the process of vaporization of the circulating blood in the living animal. Their equipment consisted of two plates of glass held 1 mm apart in a brass frame and so constructed that blood from any large vessel could be circulated between these glass plates and back again to a cannulae a little further along the same vessel. A diagrammatic example will be found in Figure 3.

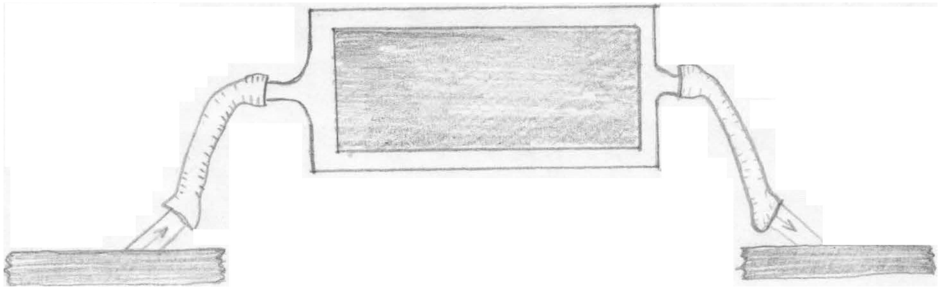
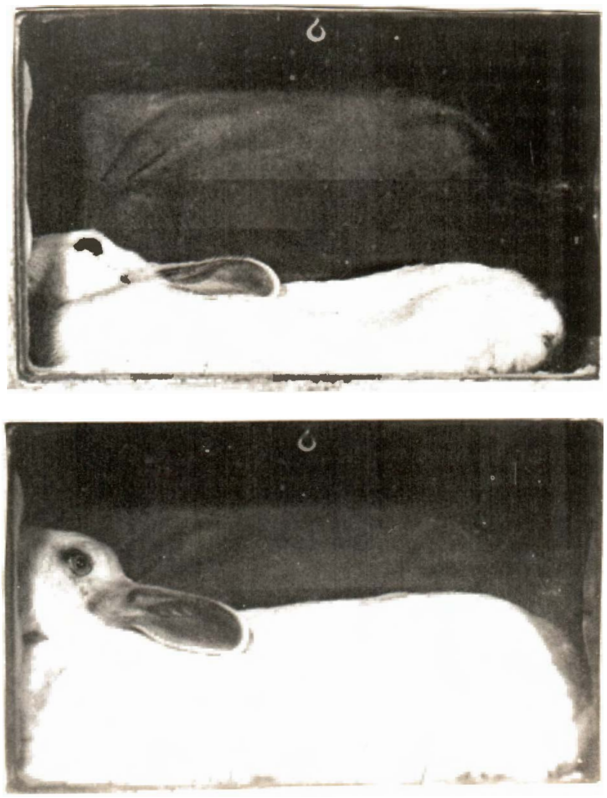


Figure 3

With the blood passing through such a cell, any bubbles could be easily seen. No visible change in the smaller animals was present until about 55,000 feet altitude was reached. At that altitude, the thin film of blood passing through the cell suddenly became somewhat grey in color. This could have been due to either dissolved gas in the blood being suddenly released or due to the formation of many microscopic bubbles of water vapor. When 58,000 feet was reached, large bubbles appeared in the circulating blood and floated slowly to the top of the experimental cell. As the ascent continued the bubbles became larger and formed faster and at 61,000 feet, a large portion of the top of the cell was filled with vapor. When 63,000 feet was reached, another sudden change occurred and within a moment the remaining blood was replaced with water vapor bubbles with an interlacing surface tension network between the bubbles similar to that present in soap solutions. The water vapor formed in the blood at high altitudes is eliminated very rapidly through the lungs if the circulation and respiration are maintained. However, as soon as either or both of these fail, the elimination of water vapor essentially stops and the body quickly becomes distended to its utmost limits. An


At sea level

At 63,000 feet

Figure 4
Distension produced in a rabbit by the formation of water vapor in the body tissues and blood at altitudes above 63,000 feet.

excellent example of an experimental animal at sea level, with a size comparison of the same animal a few minutes later after decompression to 65,000 feet with distension of the tissues with water vapor is present in Figure 4. As you will note, not only is the diameter of the animal greatly increased, but that his length has also increased. Although it isn't easily seen in the figure, the skin of the animal is very taut which limits the vaporisation process by increasing the internal body pressure until the boiling of the body fluids ceases.(3) This is the picture you would see if an airplane flying over 63,000 feet were to suddenly have a loss of cabin pressure and the occupants didn't have the benefit of pressure suits.(56) Since military aircraft must be able to fly to extreme altitudes in order to reach enemy aircraft, it is not unusual for an airplane to attain heights at which their body fluids could boil. Although commercial aircraft are finding that altitudes of 35,000 feet are advantageous in many ways, they haven't yet found it necessary to go to 63,000 feet. With the prospect of man taking to space travel in the near future, all aspects of dysbarism must be combated, as they are now in our high altitude aircraft.

The Nervous System

Any explanation of some of the symptoms of dysbarism should certainly include the effect of decreased atmospheric pressure on the nervous system. Although neurologic symptoms occur somewhat infrequently, when they occur they are often dramatic. The most frequent type is a momentary visual defect which is manifested by homonymous scotomata or even hemaniopsia, and a headache which is similar to migraine. Less commonly, a monoplegia, aphasia, transitory hemiplegia, and confusion may occur. In general the neurologic reactions differ from the other symptoms in that they often occur shortly after a flight as well as during flight.(46) There are few physicians who realize the inherent seriousness of a pathologic situation of dysbarism when the patient may initially present quite mild symptoms but may collapse or even die. A case presentation of decompression sickness at medium altitude will serve to present some of the typical symptoms in a manner in which the average physician is much more prone to recognize them again.

Report of a case

This thirty year old test pilot for the maintenance squadron at an Air Force training base, had over 900 hours of jet aircraft flying time. He had no earlier history of any symptoms of dysbarism. He noted no symptoms of fatigue or physical stress and had had five and one half hours of sleep with an adequate breakfast prior to flying. He took off at 1330 hours in a T-33 aircraft with his destination as Lowry Air Force Base, Colorado. He was in the rear seat because he was receiving an instrument check from another pilot in the front seat. The patient had no preoxygenation before take off. During takeoff and up to 5,000 feet, 100% oxygen was breathed, and then at 5,000 feet the regulator was set to a normal oxygen position. This position gives a mixture of oxygen and ambient air where the percent of oxygen increases gradually up to 34,000 feet where 100% oxygen is being breathed. Approximately 45 minutes after take off, the airplane had reached cruise altitude of 40,000 feet with the cabin pressure being at a simulated altitude of 24,400 feet. About one hour after take off, he noticed he had difficulty focusing his eyes on the instrument panel. He immediately turned his oxygen regulater to 100% oxygen, held his mask tighter against his fact and teld the pilot in the front seat to check the cabin altimeter. The pilot related that it was still 24,400 feet. After about 5 minutes of breathing 100% oxygen without significant improvement in his vision, he turned his oxygen regulator to deliver oxygen under a pressure equal to eight inches of water. In a few minutes his vision improved slightly but wasn't perfect. He had difficulty reading the total aircraft serial number which is a series of six digits. At first he had only been able to read one number at a time and couldn't even see the others. After 15 minutes on pressure oxygen breathing he could read four numbers at once but not all six. He checked his eyes separately and then together and his vision was still the same.

Nearly fifteen minutes after his first symptoms, he suddenly had a sharp pain in his left knee. Shortly thereafter he had a slight pain in his right knee and areas on both thighs that "half itched and half hurt". About ten minutes later he began to get a severe headache over his whole head, but especially behind his left eye. He then went back to 100% oxygen because of the discomfort of pressure breathing and because he had no improvement in his condition. They began to descend about one hour after the original visual symptoms had appeared and his knee pain and itching disappeared, after passing through 20,000 feet actual altitude. It was estimated that the total time spent at 40,000 feet (a cabin altitude of 24,400 feet) was about 80 minutes and he was above 30,000 feet for another 20 minutes.

When the patient left the aircraft, 1½ hours after the onset of symptoms, he noticed that he didn't have complete control of his muscles. He couldn't walk straight and was somewhat dizzy. His vision was slightly blurred. He could not speak words clearly. His thinking wasn't clear and he had some trouble understanding words. After sitting down for 20 minutes, his symptoms of knee pains, itching, and a slight cough he had developed were gone, but the other symptoms were getting worse. His headache became almost unbearable and he was transported to the hospital. He was in a deep state of depression and said that although he had no logical reason to do so, he had a great urge to cry.

A flight surgeon was called and the patient had been put on oxygen at 8 liters per minute for 15 minutes. A physical exam done an hour after hospitalization revealed a blood pressure of 110/70 mm mercury, pulse 70 per minute and regular, temperature 97.4° F., respiration 16 per minute, weight 140 pounds, height 5' 5''. The fundi were normal in appearance. Nystagmus was not present, pupillary reflexes and the extraocular movements were normal. A gross confrontation test didn't reveal any visual field defect and the patients vision wasn't blurred anymore. The neurologic exam revealed a slight weakness in the right hand. The Rhomberg test was normal, although the patient still had the sensation of staggering when walking.

He was definitely unsteady when his walking was observed and he stated that he still didn't feel well. The test for carbon monoxide drawn upon admission was negative. The urinalysis was negative. The hemoglobin was 15.7 gms% with the WBC being 8,400 per cubic mm; with 56% neutrophils, 40% lymphocytes, 17% eosinophils and 5% basophils. The sed rate was 5 mm per hour. An x-ray of the chest was normal.

In the morning the patient had only a slight headache and a feeling of general weakness with no apparent weakness in the right hand. All visual tests were normal as were the neurologic and E.E.G. tests. The following day he felt fine and was released to full flying duty. Since then he has flown the same aircraft to 40,000 feet without any difficulty. The airplane and instruments were thoroughly checked and at no time did the cabin altimeter exceed 25,000 feet. From the thorough investigation of the equipment and the progressive pattern of the patient's symptoms after he was on the ground, it is certain that hypoxia can be ruled out. The visual imparement, dysarthria, headache, staggering, weakness of the right hand and difficulty in understanding are very suggestive of multiple intracranial lesions from gas bubbles. Although no spinal tap was done, there were no signs of meningeal irritation or papilledema to give consideration to intracranial hemorrhage. The course, onset, and recovery pattern are consistent with the diagnosis of dysbarism. Although this happened at a somewhat lower altitude than most cases of dysbarism occur, aeroembolism has been known to occur at 22,000 feet altitude.(46)

Not everyone is as fortunate as he in that this was a relatively minor case of dysbarism. There are many reports of paralysis and death(24) which have occurred from dysbarism. Although lesions in the spinal cord due to rapid decompression are well known in divers and caisson workers (38), it has been less frequent in airmen. However a case of quadriplegia developed from a run in a decompression chamber whose neurologic picture was essentially the same as in the anterior spinal artery syndrome. Since fatty tissue can dissolve about 5 to 6 times as much nitrogen as water can and nerve tissue contains a high percentage of fat, it is not unlikely to have neurologic symptoms resulting from nitrogen bubbles being liberated at high altitudes. It also is likely that nitrogen bubbles from retroperitoneal fat deposits can reach the spinovertebral plexus of veins and, by obstructive action, retard the venous return from the spinal cord. This would facilitate embolization of spinal precapillaries and arterioles.

We know from clinical neurology, and it has been confirmed by studies of the brain circulation, that any irritation in or begeath the blood vessel's walls may cause extremely intensive and prolonged spasms. Thus it seems highly likely that perivascularly located, autochthonously formed bubbles in the central nervous system could induce vasospasms, causing ischemic lesions.(27)

In an early attempt to find out more about the central nervous system at high altitudes, a study was made on goats. A spinal puncture needle was inserted into the cisterna basalis of the animals and connected to a water manometer. The animals were then exposed to various altitude pressures up to 50,000 feet. At 18,000 feet altitude the spinal fluid pressure began to rise sharply and at the same time a gas bubble appeared in the short leg of the manometer. As a higher altitude was reached, more bubbles appeared and gradually worked their way through the fluid and out into the atmosphere. The spinal fluid pressure which had begun to rise was intermittantly relieved as the bubbles passed through the manometer so that it was never more than a few inches of water pressure above normal. This experiment has also been repeated on human subjects with identical results.

They then substituted a mercury manometer and measured the rise of spinal fluid pressure when the gas was confined to the space usually occupied by the spinal fluid. A graph, Figure 5, represents the rise in pressure of the spinal fluid and as you will notice that at 50,000 feet altitude the spinal fluid pressure is almost 400% over normal.

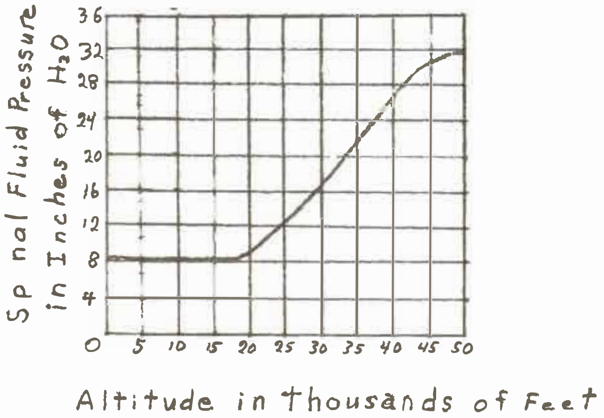


Figure 5

In certain persons a neuralgia type of pain was noticed which reappeared at the same place in the same individual during ascent to high altitudes. The reason for these pains is not definitely known, but is thought to be due to a localized pressure around a sensitive area of the nerve. This theory is based on the knowledge that a column of water exposed to reduced atmospheric pressure will increase its volume greatly as a result of the expansion of its dissolved gases. Since the sheath of a nerve trunk has a high percent of fat, and fat dissolves

The anatomy and function of the middle ear and eustachian tube is a very interesting subject but a complete discussion entails so much material, that it is beyond the scope of this thesis. However, a brief description would be helpful in orienting one in any study of aerotitis.

The middle ear is an irregular space within the temporal bone and lined with a pseudostratified columnar epithelium. It contains a chain of movable bones, which connect the lateral and medial walls and convey the vibrations which fall on the lateral tympanic membrane to the inner ear. The middle ear communicates to the nasopharynx via a slender duct called the eustachian tube. It forms an angle of about 45° with the sagital plane and one of 30 to 40° with the horizontal plane. The lateral third of the tube is a bony segment which opens into the cavity of the middle ear. The mesial 2/3 of the tube is membrano-cartilaginous in structure and opens into the nasopharynx.(21) Usually the walls of the membraneous portion are approximated due to the mucosal attraction and it normally acts as a sort of flutter valve which opens when a pressure differential exists. The tube may be opened by swallowing, yelling or yawning because of the levator veli palatini and other palatal muscles.(18)

A positive or negative pressure differential developing in the tympanic cavity will cause trauma to the immediately surrounding tissues and possibly also to the cochlea. A failure or the inability to open the eustachion tube may cause inadequate ventilation of the middle ear during changes in altitude. A failure to open the eustachian tubes while undergoing altitude changes is usually due to ignorance of the necessity to do so. However, it may be due to being asleep; to the influence of analgesics, anesthetics, or coma; or carelessness.

The inability to ventilate the middle ear voluntarily has a higher incidence than is usually recognized. A few of the more frequent causes of eustachian stenosis are acute and chronic infections of the upper respiratory tract, sinusitis, tonsillitis, nasal obstructions, tumors and growths of the nose and nasopharynx, paralysis of the superior pharyngeal muscles or the soft palate, enlargement of the pharyngeal or tubal tonsil, malposition of the jaw and inflammatory conditions of the eustachian tube, especially following adenectomy. Simpson says that it is not unusual to see considerable scar tissue around the pharyngeal ostium of the eustachian tube as the result of an adenotome passing too far laterally, and causing trauma or laceration to the torus tubarius.(3)

If one begins at sea level pressure and decreases the pressure at a constant rate, then a 3-5 mm mercury, i.e., 110-180 feet in altitude, pressure change is required before any effect is noticeable. A slight sensation of fullness and the bulging increases, as the pressure decreases until at a differential pressure of 15 mm mercury, i.e., 500 feet in altitude, a "click" like noise is heard and felt in the ear. This is produced by the eustachian tube being forced open by the pressure build up in the tympanic cavity and producing the "click". Air from the tympanic cavity had forced open the eustachian tube, passed into the nasopharynx, and removed the high pressure differential. The cycle is then repeated during ascent except that the succeeding "clicks" occur at about 11.4 mm mercury pressure differential or 435 feet in altitude. This indicates that the eustachian tube remains open until the pressure is lowered to 3.6 mm of mercury, where it closes. Due to the fact that the pressure altitude curve is not linear, the eustachian tube opens at equal intervals of altitude. This amounts to 11.4 mm of mercury at sea level but only to 3.5 mm mercury at 40,000 feet. The seeming inconsistency is probably explained by the air of higher altitudes being less dense and it passes more easily through the eustachian tube.(18)

Pressure differentials of from 15 to 30 mm mercury causes much discomfort and may cause tinnitus, which is of a steady hissing or crackling character. Above a 30 mm mercury pressure differential, there is increasing pain, tinnitus, and vertigo, which usually becomes unbearable. At about 60 mm of mercury pressure the pain in the ear is severe and resembles that of acute otitis media. From 60 to 80 mm of mercury pressure, the pain becomes very severe and radiates from the ear to the temporal region, the parotid gland, and the cheek. At still higher pressures, an agonizing pain seems to localize deep in the substance of the parotid gland, deafness is marked and vertigo and tinnitus usually increase. At a pressure of from 100 to 500 mm of mercury, the tympanic membrane ruptures in a dramatic episode in which the patient feels as though he has been hit alongside the head with a plank. A loud explosive report is felt and heard in the affected ear with a sharp piercing pain on the affected side and vertigo and nausea become severe and sometimes general shock occurs. After rupture of the tympanic membrane, the acute pain subsides, but a dull ache persists for from twelve to forty eight hours. Diminished hearing, nausea and vomiting may last for 48 hours.(3)

The Gastro-intestinal Tract

The effect of gaseous expansion in the gastro-intestinal tract will vary somewhat according to the amount of the gases present within the lumen of the gastro-intestinal tract initially and also according to the rate of ascent. Since they are saturated with water vapor, the gases contained within the gastro-intestinal tract expand at a greater rate than might be expected by BOYLE'S LAW. They will expand in a ratio derived from the formula $\frac{B_1 - 47}{B_2 - 47}$ where B_2 is the barometric pressure at the higher altitude and B_1 is the initial barometric pressure. This formula would result in an expansion of 7.6 times normal volume in a rise from sea level to 40,000 feet altitude. However, the fact that the stomach and intestinal tract are not freely expansible has not been taken into consideration in the formula. The intestinal wall would slightly increase the amount of pressure of the gas and the expansion wouldn't be quite as much as the formula would indicate. The gas expansion is nevertheless great enough to manifest symptoms. In the average person, an ascent of 200 to 300 feet per minute or less, at about 12,000 feet, will cause a feeling of moderate abdominal distension. At nearly the same time, a hypermotility of the intestinal tract usually begins with frequent intermittent gurglings being felt as the gas moves through the liquid contents of the bowel. Also a small amount of gas may be belched and an urge may arise to pass flatus from the rectum, where the gas has begun to collect. If such a slow ascent continues, the previous effects tend to continue because as the expelled gas is eliminated, it is replaced volumetrically by the remaining gas expanding, until the ascent stops. Then the gas will continue to be expelled for an hour or two until the remaining gas reaches a volume about that which it occupied before the ascent began.

If the ascent is at a greater rate, i.e., 1,000 feet per minute or more, there is a slightly different condition. In this case, the gas tends to stay localized in pockets in the intestinal loops instead of moving along and being expelled as before. For this reason, the abdominal distension is increased greatly. At about 15,000 feet altitude or above, abdominal cramps of varying severity may occur. When 30,000 feet in altitude is reached, these cramps are quite likely to be present and if the gas moves along the intestinal tract at all, it travels quite slowly. In a mild case of distress, descent may relieve it immediately, but in severe abdominal distress, often the cramps last as long as twenty four hours after descent to sea level pressure. In the healthy individual, the abdominal distension hasn't seriously embarrassed heart action or respiration. Such abdominal distension could be a hazard to an individual who had lesions of the gastro-intestinal tract, lungs or heart.(18)

Aerosinusitis

Aerosinusitis is the fourth most common cause of pain due to rapid pressure changes. If the air in the sinus is not free to flow in and out of the sinus cavity via the sinus ostium, then a pressure differential will result with changes in altitude. As a general rule, an increase in pressure will cause more difficulty than a decrease in pressure. An obstruction of the sinus ostium can occur from redundant tissue, anatomic deformities, or swollen mucosa. The frontal sinuses and the maxillary antrum are more often involved than the other sinuses because these relatively large air spaces communicate with the nasal cavity through quite small openings. When blockage of a sinus does occur, the cavity pressure to the exterior is positive on ascent and negative on descent. This pressure differential causes trauma to the sinus epithelial lining which in turn begins to swell and become edematous. Pain is severe and usually localizes in the frontal area. Local tenderness may be present over the sinus. These symptoms agree with the accepted view of referred sinus pain. In review, any person who has sinusitis, polyps in the sinus area or any abnormality in the region of the sinuses shouldn't fly until these conditions are remedied.

Aerodontalgia

Aerodontalgia is a painful condition of the teeth and neighboring tissues which is caused from a decreased atmospheric pressure. Although it is not common, its incidence is high enough that it merits some mention. In a study of fighter pilots who are not infrequently exposed to low barometric pressures, almost 10% of them were reported to have had aerodontalgia. This toothache at high altitudes is often caused by a cavity in the pulp which would probably have caused the same symptoms without decompression. Usually the pain is worse when a greater and rapid lowering of barometric pressure occurs. This pain is usually relieved by recompression. The pain often reoccurs if the individual is again decompressed.

Other Factors

There are many other factors which must be included under the physiological effects of reduction in barometric pressure. Some are at present unknown and the degree of influence which many of the others have on man is still largely undetermined. Some of the research being done in this regard bears noting and is of importance in furthering the safe and rapid advance of aerial navigation.(33) Pilots should be physically fit as determined by a physical examination.(12) However, we must realize that many of the passengers will not be in good physical condition and health. In older people, coronary insufficiency may be one of the major considerations in decompression sickness.

There are many factors which have to be taken into consideration in determining the qualifications for a good flier. For example, flyers can be grouped into the two general classes of fainters and non-fainters. High altitude will usually cause an increase in depth of respiration and an increase in volume per minute. This causes a decrease in the carbon dioxide pressure in the alveoli. This in turn causes a decreased amount of carbon dioxide in the blood and disturbs the chemical ratio maintained between the carbonic acid and the bicarbonates. Thus, because of this washing out of carbon dioxide, an alkalosis results and a chemical condition results which is unfavorable to the dissociation of oxygen to the tissues. This added to the fact that there is usually a less than normal partial pressure of oxygen in the alveoli, may cause the flyer to faint. There is normally a gradual increase in the pulse rate and there may be a slight increase in the pulse pressure. In a fainter, there is usually a great increase in systolic blood pressure, with a sudden break in the pulse or blood pressure which may cause fainting. There are many such tests which are available if there is great need to determine if an individual is well adapted for flying. However, physical constitution seems to have little to do with an individual's capacity to tolerate the mental stresses of flying, unless the individual is over-taxed physically.(29) In general, flyers become fatigued more as a result of emotional stress than as the result of physical agents such as cold, or toxic agents or lack of oxygen.(59) The gastric secretomotor activity and the renal excretion of uropepsinogen during periods of high altitude flight become greater than usual and is one representation of the physiological effects of fatigue.(28) Tests have been done on the urinary excretion of 17-hydroxycorticosteroid levels during high altitude flights in a B-52. When compared with the control specimens of the individual, the 17-hydroxycorticosteroid urinary output was almost two times as great during the high altitude flight. This thus seems to be a good index for measuring stress in flying personnel.(34) The fact that the body seems to be under a great amount of stress at high altitudes may make the body less able to fight infections. An experiment by Altland on dogs showed quite conclusively that dogs exposed to high altitudes become quite susceptible to bacterial endocarditis if exposed to the etiological agent, while the dogs remaining at low altitudes and exposed to the etiological agent in the same manner, remained resistant to bacterial endocarditis.(1)

Although man utilizes a pressurized cabin at high altitudes to prevent dysbarism, if he has to suddenly bail out of his plane at about 40,000 feet, he would be subjected to the problems of dysbarism.(10) Probably a compromise between the physiologic ideal of full body pressurization and the necessity for life could become necessary. A pressure oxygen breathing mask which would maintain an absolute pressure in the lungs of 141 mm of mercury would give short term protection against those altitudes and enable emergency descent to be made.(43)

The escape from high performance aircraft by the use of the ejection seat has resulted in the saving of many lives. Still there is an incidence of 23% mortality and a 14% major injury at present.(37) Dysbarism hasn't been the major problem, but it has been a problem in some. Mechanical difficulties are important and high velocity winds with no protection can also result in fatalities.(41)

For each 1,000 feet rise above sea level, as a rule, the average atmospheric temperature falls about 2° C. until 35,000 feet is reached. Above 35,000 feet the temperature remains almost constant at -55° C., at least to 80,000 feet and possibly beyond. This is a problem with which man must cope in order to live in the high altitude environment.(3) Research has been fruitful in providing man with light weight clothing and various forms of artificial heating.(49) This problem also exists in bail-out at high altitudes because the individual could die as a result of frost bite, if he didn't freeze to death before landing. Armstrong feels that breathing very cold air doesn't cause frost bite to the respiratory tract, but that the individuals body must be kept warm.(4) This fact is important in that in a high altitude pressure cabin atmosphere, the whole cabin doesn't have to be kept very warm. Electrically heated suits may be used which reduces the weight of heating equipment considerably where it is necessary to reduce weight.(49) These many signs and symptoms and facts about dysbarism are very helpful to a physician or anyone who is concerned with its problems.

Treatment

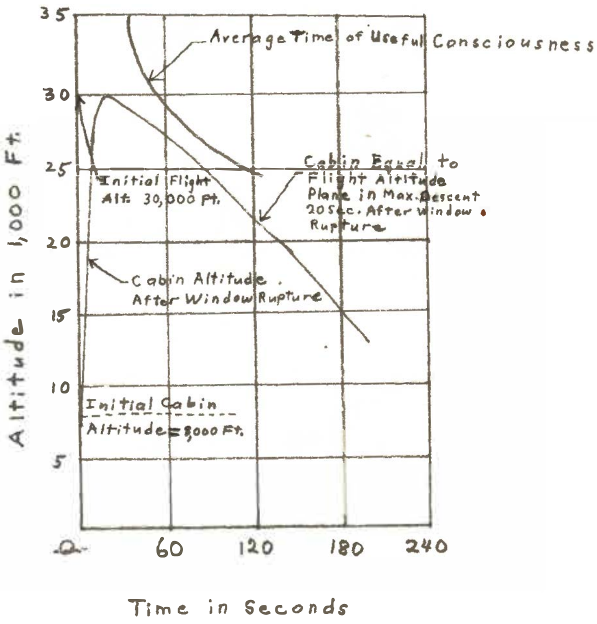
The best way to avoid the problem of dysbarism is to employ the best available methods of prophylaxis. This includes education, pressurized cabins, flying suits, denitrogenation, good health, and the proper equipment. If the signs and symptoms of dysbarism do occur, it behooves physicians in this "air age" to be able to recognize them as such and to give the best medical treatment available.

Ignorance is a factor in many cases of dysbarism. If people are educated in some of the basic principles, they can do much to prevent problems from arising. For example, many people don't know they should periodically swallow during rapid changes in altitudes in order to alleviate discomfort from aerotitis. Some people are not educated to the fact that they should not be subjected to barometric pressure changes if they have an upper respiratory infection or a nasal polyp. In cases of necessary air travel, when they have upper respiratory infections, most people do not realize it would be much safer if they were given vasoconstricters prior to flying. Few people realize that they shouldn't eat or drink gas forming substances prior to flying to help eliminate abdominal distention and discomfort at high altitudes.

is thus gradually lost from the body.(32) There have been some that feel that a 50% oxygen-helium mixture should be used to eliminate the high inflammability of 100% oxygen. Careful experiments have been done to determine various factors in denitrogenation and most of them agree fairly well. The human body is determined to have between 1 and 1½ liters of dissolved nitrogen. Denitrogenation by breathing 100% oxygen at ground level for fifteen minutes will reduce the incidence of bends and chokes by approximately 50%. Denitrogenation at altitudes up to 20,000 feet is as effective as at ground level. Still, denitrogenation will not prevent abdominal distention or aerosinusitis, aerodontalgia, or aerotitis. Decompression or return to lower altitudes is still the best treatment. This causes an equilibration of pressure differentials which exist. It decreases the volume of gas in the intestinal tract as well as reducing the size of gas emboli and bubbles in tissues, according to BOYLE'S LAW. Recompression thus accomplishes an important objective in the treatment of "bends" or aeroembolism and chokes, in restoring the normal blood supply by reducing gas emboli.(8)

If a physician sees a patient who had typical symptoms of the bends in the air, a good differential point is that most of the chokes and bends symptoms usually leave after the patient is decompressed below 20,000 feet altitude. However, the symptoms of gas emboli in the central nervous system, malaise, and other vague symptoms, may persist after landing. Although recompression is the most specific treatment for dysbarism, the patient should be further treated for any complications which have arisen. In a case resulting in neurocirculatory collapse or shock, the usual regimen for shock, including plasma expanders and blood, may be needed. Oxygen can be used as needed and rarely does any harm. Some patients who are hypertensive are benefited by antihypertensive drugs. Coronary insufficiency is a complication not rarely seen in older individuals and should be treated according to the best therapeutic measures available for this condition. Subjects may also develop cardiac arrhythmias and this should be treated as a serious condition. Occasionally decompression sickness can clinically resemble acute cor-pulmonale. Since it appears that aerodontalgia occurs in only potentially painful teeth, a careful dental examination including x-rays to reveal dental abscesses, cavities, and defective fillings is in order.(18)

In case of sudden decompression, emergency measures should be present which can be used as prophylaxis. Partial pressure suits would probably be adequate for the flying personnel, if they have been instructed in its use, and if the plane wasn't at altitudes above 40,000 feet. This would not be adequate for everyone because there is over a 20% failure in the people who try to use them.(40) In most instances of decompression in civilian aircraft, the best recourse is to make emergency descent to lower altitudes. The average time of useful consciousness at 30,000 feet is less than one minute, but if emergency descent is made according to Figure 6 below, useful consciousness is not lost and most of the problems of dysbarism would be avoided.(6)



Decompression profile involving a 20 second descent.

According to experiments, good physical training can improve altitude tolerance by about 3,000 feet and altitude acclimatization causes a further improvement of similar magnitude. While this is not practical in most instances, it may be benificial in specific cases.(5)

Poor general health increases a number of problems which can be encountered at high altitudes. If a person has cardiac or lung disease, a combination between abdominal distension and low barometric pressure can cause the patient to become dyspneic.(45) Chronic bronchitis, asthmatic bronchitis, and bronchiectasis, unless severe, do not bar flying. Since atopic and non-atopic asthma is a relatively common condition, a few words should be mentioned in regard to travel by air.(23) Asthmatics who develop emphysema probably shouldn't fly unless necessary, especially if there are large blebs present which could rupture. Most patients with asthma may fly, preferably in pressurized planes and using their proper medications when necessary. Asthmatic patients may find some relief during their pollen sensitive period, if they fly above 6,000 feet, because pollens aren't found above this altitude. Their vital capacity should be above 50% of the calculated value and patients with status asthmaticus shouldn't be flying. Asthmatics (as a rule) should not

Explosive Decompression

If the pressure cabin of an aircraft should fail, either due to compressor failure or structural damage, the occupants who experience the sudden change in environment may suffer serious consequences. At first, the rate of air flow through any defect in the cabin may reach such a high value that anyone near the defect may be explosively ejected from the airplane. It has been convincingly demonstrated that a dummy man, correct in size and weight, can be completely ejected from his seat in the event of loss of a window in a large volume pressure cabin. There are several cases which have been reported of actual loss of individuals by this mechanism. Then the occupants would be subjected to high velocity air currents at a temperature around -50° C., with resultant damage to them and their personal equipment.

The time of effective consciousness would be less than half a minute. This is not totally due to the lack of oxygen supply, because the time available would be some 30% less than would occur in the event of just a loss of oxygen supply.(19) A very important measure to enact, however, would be to use oxygen and make an emergency descent to lower altitudes.

Tolerance to rapid decompression is generally agreed to be limited by the ability of the lungs to withstand sudden pressure changes.(26) Because of their delicate structure, the lungs are more susceptible to injury as the pulmonic air expands in accordance to BOYLE'S LAW. It has been shown that the mammalian lung will rupture if overdistended with a transthoracic pressure gradient greater than 80 mm of mercury. If the airways are unobstructed at the moment of decompression, the gas will begin to excape from the lungs immediately, and thus reduce the pressure gradient across the chest wall. Although serious casualties usually don't occur in rapid decompression with open airways, there may still have been some structural damage to the lungs.

The pressure differential which causes the damage can be resolved into two principal determinants. The first is the "time characteristic" and is dependent upon the geometrical and aerodynamic features of the container and the decompression orifice.(3) Haber and Clamann formulated Tc, the time characteristic(17), into the general form $Tc = \overline{A \cdot C}$ where V is the volume of the lungs, A the area of the effective orifice and C the velocity of sound. The velocity of sound was introduced as a characteristic of the rate of flow, to eliminate the effect of density.

The other determinant is the fractional differential of decompression (P') and is a complex function of the initial and final pressures formulated as follows: $P' = F\left(\frac{P_i - P_f}{P_i}\right)$ where P_i is the initial absolute pressure and P_f is the final absolute pressure. This fractional differential for any combination of cabin and flight altitude can easily be read from a chart made from the formula or taken from the article by Luft and Bancroft.(31)

When the airways are closed at the beginning of rapid decompression, the lungs act as a closed container and the intrapulmonary pressure increases as a function of the initial gas volume of the lungs. This rapid elevation of the intrapulmonary pressure may reflexly cause apnea, bradycardia, and a lowered blood pressure. Clinically, the vasomotor and neurologic findings may simulate those seen in the neuro-circulatory collapse of divers decompression sickness, a disorder believed to be related to the evolution of body gases following long exposures to low barometric pressures. However, the collapse seen during rapid decompression at high altitudes is caused by the mechanical effects of the expansion of trapped gases in the lungs. This rapid elevation of intrapulmonary pressure probably stimulates the vagal receptors and causes an exaggerated Herring-Breuer reflex. Benzinger believes that the neurologic findings are due to cerebral air emboli.(26)

With a high pressure differential between the lungs and the pleural space, often a thin walled alveolae may rupture. This damage may cause hemorrhage by tearing blood vessel walls, and gases from the lung may escape into the adjacent tissue planes. When alveoli, which rupture, are lying near large blood vessels or air passages, the escaping gases may follow along these structures and the result is the passage of gases to the root of the lung, the mediastinum, the neck, axillae and retroperitoneal spaces. Another important concept in the etiology of lung damage, after explosive decompression, is that of unequal ventilation of the lung. It appears that different areas of the lung loose their excess gases at different rates, because of the varying size of air passages. Thus there may be local areas of excessive pressure built up which may lead to alveolar rupture. If this occurs in the vicinity of vessels unable to completely collapse, some of the gas may be forced into the vessels with resulting gas embolism. This is another source of gas emboli.(19)

In a situation where an individual is breathing oxygen through a mask or helmet and not wearing a full pressurized suit, it is easy to see the necessity for having an emergency relief valve which automatically dumps the mask or helmet pressure, in decompression emergencies. Otherwise the air in the lungs wouldn't be allowed to come out rapidly and reduce the pressure differential.(30)

Although man has participated in many experiments involved in rapid decompression, the pressure differential has been of a fairly mild degree in all but a few cases. In any explosive decompression which involves a great pressure differential such as from sea level to 65,000 feet simulated altitude, there is so much pathologic destruction that only animals have been used. Some very exacting work has been done on rats explosively decompressed in 8 to 12 milliseconds, from sea level to 65,000 feet simulated altitude, and then fixed in formalin at the 65,000 foot level by men wearing full pressure high altitude suits. Then the rats were sent to the Armed Forces Institute of Pathology for pathologic study. It is significant that total fixation of the animals occurred at altitude and the gross and histologic findings were the result of explosive decompression alone, without the artifact of recompression.

After sudden decompression, the rats rose on their hind legs, gyrated, and expired convulsively almost immediately. It appeared that death was due mainly to the trauma rendered by the expanding internal gases. In all the animals there was extensive emphysema extending to the thoracic wall and containing large sacs of air. The skin and subcutaneous tissues were separated from the pectoral muscles, which in turn were separated from the rib cage. Although the heart was compressed against the xyphoid, no rupture of the heart and major vessels was found. Much other severe pathologic damage was present, such as rupture of the diaphragm and separation of the kidneys from the posterior perinephric fat beds. The major damaging effect of such an explosive decompression apparently is due to the rapid accumulation of gases by dissolution from tissues, and the expansion of gross gas.

This pressure differential of 14.7 /.823 p.s.i. is within the range where a non-elastic response of tissue occurs. The theory that there are long coiled chains of protein molecules in elastic tissues, which require that they have sufficient time to uncoil in order to respond elastically, may be true and operative in this case.

The most probable causes of death in the order of probable occurrence could be: 1) acute cardiac dilation,

2) the ram effect of expanding gross gas and 3) multiple hemorrhages and the breakdown of tissues of vital organs.(20)

From this concept a disturbing consideration arises. It is estimated that a total and sudden loss of the canopy of a military aircraft would result in an equalization of ambient and cockpit pressure in about 12 milliseconds.(17) If the aircraft were flying at extreme altitudes with the standard cockpit pressurization, the pilot might encounter pressure changes rapid enough to cause severe gross and microscopic damage.(20) As the future brings flight at extreme altitudes, there should be a protective garment capable of assured protection in explosive decompression, if total protection for the aviator is contemplated. Also, since materials subjected to pressure vary in their ability to withstand explosive decompression, all materials used should be tested for strength against decompression.(36)

As a general rule, man will not be flying at such extreme altitudes that he would be subjected to pressure differentials where he would be severely injured, should explosive decompression occur. Most of the serious complications have arisen when man's airway was closed due to swallowing, holding the breath, or being at the peak of inspiration. At lower pressure differentials, such as in altitude chambers and at altitudes below 40,000 feet, there would probably be few serious casualities from sudden decompression provided the airways were open and proper emergency steps instituted.

The Future

As the skies are becoming cluttered with unmanned satellites, sending back data useful to the space scientists, man himself is preparing for a journey into space. The U.S. intelligence believes the Soviets may put a man into space in the near future, and within a year if everything goes according to plan, the United States will launch its own volunteer. The machine which may take the first United States astronaut into space is the fabulous rocket-powered X-15. It looks more like a guided missile than a plane and is designed to fly at speeds up to 5,000 miles per hour and altitudes of 200 miles, Scotty Crossfield, the test pilot for North American Aviation, who is building the X-15, is confident of the ability of man to travel in space. He feels that each generation has imposed limits upon itself and then have never failed to vastly exceed these limits. He said "Barriers exist only in the minds of men" and providing the money is made available, we will be traveling to the moon sooner than we think. Captain Iven Kincheloe has already flown the rocket plane X-2 to the present worlds altitude of 126,200 feet.(11)

The idea of life on other worlds is a subject which captivates the imagination of man. After 1543, when

Copernicus discovered that the earth was not the center of the universe and there were other planetary members of the solar system, thoughts of other worlds began. Man has constantly tried to get a closer view of these celestial bodies. The invention of the telescope about 350 years ago brought a closer optical view, and recently the successful development of rockets has the potentiality of taking us closer to them physically. Atomic power may also be a source of energy which will be utilized to take man into space and perhaps to another planet.(53)

The atmosphere of the earth can be considered for practical purposes, to extend to 120 miles with about 99% of its mass within 20 miles of the earth. The remaining 1% may extend to 60,000 miles beyond the earth. Since man has conquered atmospheric flight and space equivalent flight, the next step will be circumplanetary flight at the outer fringes of the atmosphere. Such a flight has many attendant medical problems, such as dysbarism. Most of these problems have been analyzed and solved. The break-off phenomenon, which is a feeling of physical separation from the earth when piloting an aircraft at extreme altitudes is now being investigated. Following earth satellites flights and unmanned lunar probes, the next goal of man could be the Moon or Mars.(13)

Venus and Mars are the closest planets to the Earth, with Venus six minutes away at the speed of light and Mars twelve and one half minutes away at the speed of light. Since Venus has a thick cloud cover and nothing about its surface is known, Mars will probably be given attention first. The conditions on the surface of Mars are very similar to stratospheric conditions 11 miles above the Earth's surface.(57)

Since the barometric pressure on Mars at ground level (there is no open water on Mars) is about 70 mm of mercury and corresponds to an altitude of 55,000 feet in our atmosphere, the astronaut will have to wear a pressure suit to leave the environment of his space ship. Although there is some debate as to the possibility of wearing a partial pressure suit for short periods at this altitude, he would have to have some form of pressurization to prevent the problems of dysbarism. If a leak occurred in his sealed compartment or the pressure suit, the astronaut on Mars would be subject to rapid decompression and the effects of dysbarism. He wouldn't, however, be subjected to "ebullism", which is the term for the boiling of body fluids, which occurs above 63,000 feet altitude in our atmosphere. Health hazards from cosmic rays don't seem to be as great a danger as once thought. The temperature would be almost as cold as it is at about 55,000 feet altitude and he would need protection. Thus the future seems to indicate that dysbarism will become more and more important in the "space age".(53)

Summary

In this "air age" man has greatly increased his travel by air and is now reaching into that infinite space beyond the earth. As man goes higher and higher above the earth, the barometric pressure gradually decreases. The term "dysbarism" includes all the physiological effects of a reduction in barometric pressure, independent of any effects of hypoxia. If the physician has an understanding of the etiology, signs, symptoms and treatment of dysbarism, he will then have a firm foundation upon which to build his knowledge of aviation medicine.

It behooves all physicians to become aware of some of the problems which this new environment imposes upon its inhabitants, because the physician of today and tomorrow will find that his air-traveling patients require he know more and more about aviation medicine. The symptoms, some of which have been known under such names as bends or decompression sickness, may be mild, severe, or may even cause paralysis and death.

The effects are mainly due to the expansion of free gases in certain body cavities from which the gas cannot readily escape. This expansion puts undue pressure on the wall of the cavity with resultant stretching and

pain and sometimes a pathologic change occurs. The effects are also due to evolved gases, principally nitrogen, which escapes from solution into the blood and tissue fluid and may give rise to bends, chokes, and neurological symptoms.

A review of certain physical laws such as BOYLE'S LAW, PASCABS PRINCIPLE, DALTON'S LAW, the GENERAL GAS LAW and certain other definitions and concepts is helpful in understanding the physiological effects due to gas when there is a reduction in barometric pressure. If you have ever noticed the bubbles which form in a bottle of soda pop when the cap is removed, you have noticed the phenomenon of HENRY'S LAW. This same phenomenon may happen in the human body when the barometric pressure is rapidly decreased. These bubbles present in the body may cause pain or occlude blood vessels in the brain and elsewhere and cause signs and symptoms of dysbarism.

At 63,000 feet altitude there is such a low barometric pressure that the body fluids will boil if exposed to this altitude. There are many problems of dysbarism which if properly gaurded against or effectively treated, will present little or no problem. However, the physician must be aware of them before he can effectively instruct and treat his air-traveling patients.

Conclusion

Man has been constantly pushing back new frontiers and with these frontiers come new problems. As the years have passed, man has reached higher and higher into an environment which has been less and less favorable to life. Even before man made his first ascent in a smoke filled balloon, he had encountered the effects of a reduction in atmospheric pressure while diving into the sea for food and crossing high mountains. By his tireless research and investigations, man has gradually removed many of the obstacles he has encountered.

When man began to utilize the air for transportation, a need arose for physicians who were able to treat illnesses which occurred in individuals who were flying. These physicians were termed "flight surgeons" and they were required to have special training in the physiological problems which occurred at high altitudes. Air transportation has been greatly increasing in the past generation, and the physician of today and tomorrow will find his air-traveling patients require that he know more and more about aviation medicine.

The world wars and incidents like the Berlin Airlift have shown us that travel by air and "command" of the air is as important today as sea travel was fifty years ago. The wars have also stimulated much needed research into dysbarism and other high altitude problems.

We should pay tribute to such great men as Pilatre de Rozier, Paul Bert, the Wright brothers, and many others, who by investigation and research into the many aspects of flying, have made the air a safer place in which to travel. As man is preparing for a journey into space, we must realize that there is yet much to be done in order that we might solve dysbarism and other such problems in the rapidly approaching "Space Age".

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