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THE EFFECTS OF OXYGEN DEPRIVATION (HIGH ALTITUDE) ON THE HUMAN ORGANISM

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Part I —INTRODUCTION

I The Necessity of Studying the Effects of High Altitude in Aviation

The most important physical variables which affect the human organism while in flight in the modern commercial aeroplane appear to be vibration, noise, ventilation, temperature, rate of ascent and descent, and altitude The zones of passenger comfort and discomfort in these and other variables are shown graphically in Figure 1 (from Bassett) With the possible exception

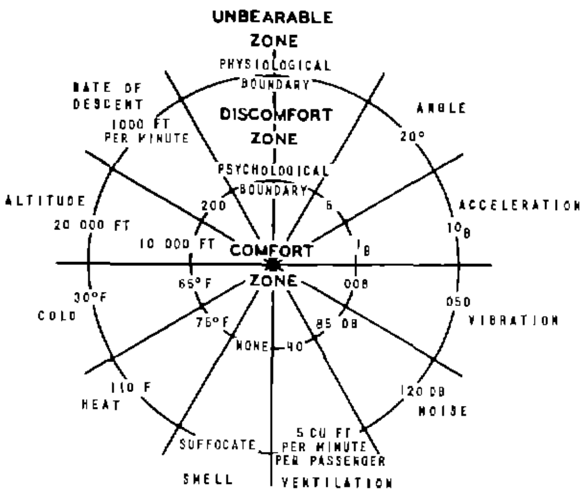

Figure 1 —Physical variables relating to passenger comfort (Bassett)

of rate of descent and altitude, these factors have been brought well within the so-called comfort zone Their elimination as unpleasant aspects of flying will soon be brought about by the skill of technical engineering The most important physical variables which remain to be controlled appear to be the physiological and psychological impairment resulting from the lack of oxygen available for the organism at high altitude and the action of sudden changes in barometric pressure on the eardrum of the middle ear These two problems are also intimately tied up with engineering skill, for their solution lies in the development of supercharged cabins This equipment, however, will not be available on a large scale for some time, and many doubt the practicability of such procedures for flights of short duration in domestic air transportation

This report is concerned with the effects of the diminished partial pressure of oxygen encountered while in flight at high altitudes on the average flying population The development of the human organism has for the most part taken place relatively close to sea level There are millions of people who have become acclimatized to altitudes as high as 8,000 to 14,000 feet in the mountainous regions of the Andes, the Alps, and the Himalayas However, transporting the human body by aeroplane to similar altitudes, even though for short periods of time, cannot help but have marked effects on various organic functions In spite of the amazing capacity of the human organism to adjust to sudden changes in the physical environment whether it be extremes in temperature, in humidity, in the ionization of the air, or in the barometric pressure and the consequent alteration in the available oxygen supply to the tissues, the problem demands thorough scientific analysis The eventual success of commercial air transportation, in competition with other means of travel, appears, among other things, to be intimately associated with maintaining a relatively normal organism during and at the end of each flight

Physiologists have been interested in the effects of high altitude for many years A number of extensive investigations have been carried out during varying periods of acclimatization in mountain expeditions, notably those of Haldane, Henderson, and Schneider (18) to Pike's Peak (1911), of Barcroft et al (2) to the Peruvian Andes (1922), and of Dill et al (17, 38) to the Chilean Andes (1935). In the Alps extensive investigations have been carried out by Mosso (51), Zuntz (70), and Loewy (40). More recently Hartmann (29) has made studies at very high altitudes in the Himalayas. There is also an extensive amount of data available from the experiments of the physiologists and psychologists who selected the pilots for altitude flying during the World War with the rebreather apparatus and low-pressure chamber. In addition there is an extensive literature dealing with many specialized aspects of the effects of oxygen deprivation in chamber experiments with rebreathing devices and with Douglas bags. Although the data from all of these sources are relevant, the experimental procedures have not duplicated the specific rates of ascent and altitudes which are experienced by passengers during the average flight on the domestic air lines.

In this report, therefore, an attempt has been made to observe the physiological, biochemical and psychological changes associated with varying rates of ascent and lengths of exposure to altitudes of 10,000 to 18,000 feet. Approximately 200 subjects varying in age from 18 to 72 years were tested individually. For the most part they were of average physical fitness with the exception of the group of psychoneurotics whose chief complaints related to chronic exhaustion and fatigue. On account of convenience and expense, the experiments have been carried out in a low oxygen chamber at sea level. These findings have been compared with the data from a limited number of experiments in a low-pressure chamber and during actual flights at high altitude. Thus far we have attempted to study only the effects of the most important variable of high altitude, namely, the diminished partial pressure of oxygen. Further experiments should be carried out during actual flights to high altitude to observe whether the changes in total pressure will give results significantly different from those obtained from alteration in the partial pressure. It is also important to determine whether the psychological effects of flying due to fear, etc., will significantly alter the data obtained from chamber studies at sea level.

II. The Physical Factors of the Environment at High Altitude

The air which is inspired at sea level contains by volume, and on the dry basis, 20.93 percent of oxygen (O_2), about 78 percent of nitrogen (N_2), 0.04 percent of carbon dioxide (CO_2), and about 1.0 percent of the inert gases, argon, neon, xenon, krypton and helium. Since oxygen constitutes about one fifth of the air, the partial pressure of oxygen alone, therefore, is 159 mm. Hg. As one rises above the level of the sea, the pressure of the atmosphere falls (barometric pressure) so that at any given altitude the concentration of gases in a given volume of air is reduced. At 19,000 feet, for example, although the composition of the air is unaltered,[1] the total atmospheric pressure and the partial pressure of oxygen are reduced one-half. The partial pressure of oxygen in the lungs is less than half that at sea level, also atmospheric air becomes saturated with water vapor at 37° C. as it reaches the alveoli of the lungs regardless of the barometric pressure. Thus 47 mm. of pressure must be deducted from the 760 mm., giving us dry air in the depth of the lungs at a pressure of 713 mm., a reduction of about 6% at sea level. When the barometric pressure is one-half normal, the diluting effect of water vapor will be twice as great as at sea level. There is a reduction of oxygen percentage from that in the atmosphere to that in the alveoli (due to dilution by the residual air of the lungs) of one-fourth or even one-third. We have, therefore, at sea level in the alveoli an oxygen percentage of 14 to 15, and an oxygen pressure of 103 mm. Hg on the average. The partial pressure of the oxygen of alveolar air normally is greater that that of the blood stream, resulting in a flow of oxygen from the alveoli into the blood where it is held in combination in the blood cells by means of hemoglobin.

Table 1 shows altitude in relation to the barometric pressure, the partial pressure of oxygen in the atmosphere, the partial pressure of oxy-

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[1] In the recent stratosphere experiments of Captain Stevens, sampling of the atmosphere indicated that the composition of the air is practically unchanged up to an altitude of approximately 14 miles.

gen in the alveolar air, and the percentage of oxygen available for the organism

TABLE 1

Altitude	Barometric pressure (mm Hg)	O_2 pressure (mm Hg)	O_2 pressure in alveolar air (mm Hg)	Equivalent % O_2 in air diluted with N_2 at sea level
Sea level	760	159	103.0	20.93
6,000	602	126	78.0	16.58
10,000	506	106	63.5	13.94
14,000	444	93	53.0	12.23
18,000	380	80	45.0	10.46
22,000	328	71	36.0	9.03
26,000	253	53	20.0	6.97
30,000	230	47	---	6.33

The relationship between altitude, barometric pressure and the percentage of oxygen available

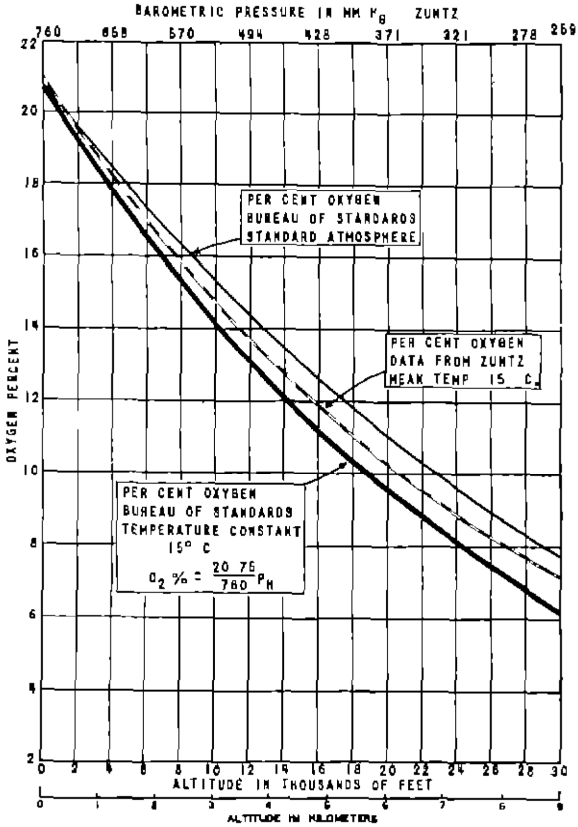

Figure 2—Comparison between altitude and oxygen percent (Zuntz and U S Bureau of Standards)

for the organism is shown in Table 2, both for the standard atmosphere and at a constant temperature of 15° Centigrade (data from U S Bureau of Standards) A comparison between

TABLE 2

Relation of Altitude, Pressure, and Oxygen

U S Bureau of Standards Data

Altitude (feet)	Air temperature (° C)	Pressure (mm. Hg)	Temperature constant, 15° C	Standard atmosphere
0	15.0	760.0	20.75	20.75
1,000	13.0	732.9	20.01	20.15
2,000	11.0	706.6	19.29	19.58
3,000	9.1	681.1	18.60	18.99
4,000	7.1	656.3	17.92	18.43
5,000	5.1	632.3	17.26	17.88
6,000	3.1	609.0	16.63	16.63
7,000	1.1	586.4	16.01	16.82
8,000	−0.8	564.4	15.41	16.31
9,000	−2.8	543.2	14.83	15.81
10,000	−4.8	522.6	14.27	15.32
11,000	−6.8	502.6	13.72	14.84
12,000	−8.8	483.3	13.20	14.38
13,000	−10.8	464.5	12.68	13.93
14,000	−12.7	446.4	12.19	13.49
15,000	−14.7	428.6	11.71	13.05
16,000	−16.7	411.8	11.24	12.63
17,000	−18.7	395.3	10.79	12.22
18,000	−20.7	379.4	10.36	11.82
19,000	−22.6	364.0	9.94	11.43
20,000	−24.6	349.1	9.53	11.05
21,000	−26.6	334.7	9.14	10.68
22,000	−28.6	320.8	8.96	10.32
23,000	−30.6	307.4	8.39	9.97
24,000	−32.5	294.4	8.04	9.63
25,000	−34.5	281.9	7.70	9.30
26,000	−36.5	269.8	7.37	8.97
27,000	−38.5	258.1	7.05	8.65
28,000	−40.5	246.9	6.74	8.35
29,000	−42.5	236.0	6.44	8.03
30,000	−44.4	225.6	6.16	7.76
31,000	−46.4	215.5	5.88	7.48
32,000	−48.4	205.8	5.62	7.20
33,000	−50.4	196.4	5.36	6.94
34,000	−52.4	187.4	5.12	6.68
35,000	−54.3	178.7	4.88	6.43
36,000	−55.0	170.4	4.65	6.15
37,000	−55.0	162.4	4.43	5.86
38,000	−55.0	154.9	4.23	5.59
39,000	−55.0	147.6	4.03	5.32
40,000	−55.0	140.7	4.01	5.08

the U S Bureau of Standards data and the Zuntz data of the relationship between altitude and oxygen percent is shown graphically in Figure 2 At 14,000 feet, for example, where the barometric pressure is 490, the percentage of oxygen available for the organism at 15° Centigrade is only 12 A number of well-known cities and mountain peaks have been charted in Figure 3 in relation to the various stations established by the International High Altitude Expedition to Chile (1935) (Cf 38, 44)

The original contention of Paul Bert (1878) has been amply verified by subsequent research, namely, that the important factor in high altitude which causes the abnormal symptoms in the organism is the diminution, not in the mechanical or *total* pressure, but in the diminished *partial* pressure of the atmospheric oxygen and

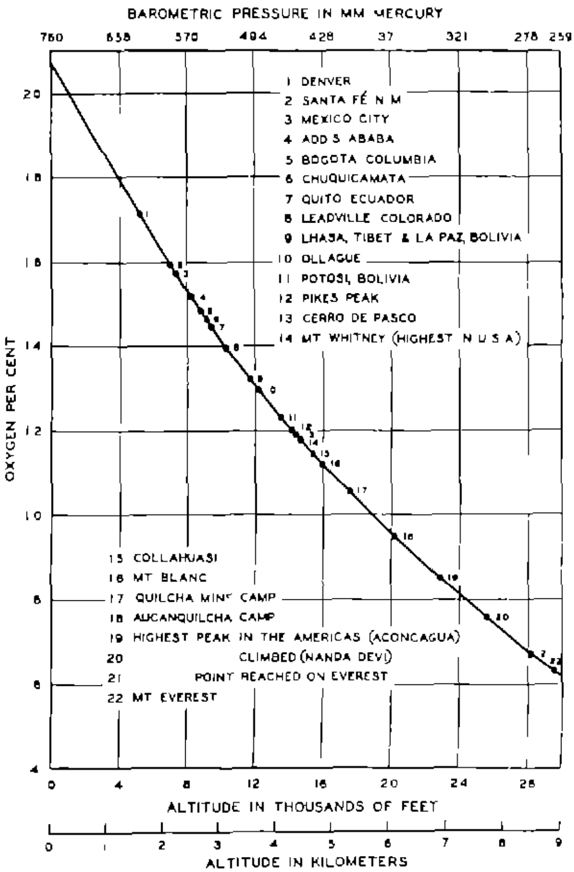

Figure 3—Comparison between altitude, barometric pressure, and oxygen percent (Chilean Expedition, 1935)

the consequent decrease in the alveolar oxygen and oxygen saturation of the arterial blood In other words, he demonstrated quite conclusively that the physiological action of oxygen and other gases depends on their partial pressures In a series of experiments on animals (chiefly sparrows) (Figure 4), Bert proved that death was due either to increased pressure of carbon dioxide or to diminished pressure of oxygen At ordinary pressure, and with ordinary air enclosed in the vessel (Figure 4), death occurred when the oxygen percentage fell to about 3 5 or when the carbon dioxide reached 26 percent At half the ordinary pressure, 7 0 was the fatal oxygen percentage so that the partial pressure of oxygen was the same, and so on down to pressures of a third and even a fourth of an atmosphere The cause of death depended simply on whether 3 5 percent of an atmosphere of oxygen or 26 percent of an atmosphere of carbon dioxide was reached first The mere mechanical pressure had no observable influence Bert repeated these experiments on himself under less extreme conditions and obtained similar results If, for example, he breathed excess oxygen from outside the chamber through a tube (Figure 4), but varied the barometric or total pressure in the chamber, he remained normal until simulated altitudes of 30,000 to 35,000 feet were reached These findings have been verified on numerous occasions by Haldane (28A), Schneider (65), and others, and it is generally accepted that the ill effects of altitude are primarily due to the diminished oxygen pressure

The above interpretation of the cause of mountain sickness was challenged by Mosso (51) twenty years later (1898), who maintained that as a physical consequence of the low atmospheric pressure more carbon dioxide was washed out of the blood in the lungs (acapnia) and that this was the most important cause of mountain sickness Subsequent research has clearly established the fact, however, that the excessive loss of carbon dioxide which occurs at low atmospheric pressure is due to the increased breathing caused by the lack of oxygen Acapnia, therefore, although an important contributing cause, is only a secondary result of the lowered oxygen pressure Cf Haldane (28A) Henderson (30), and Schneider (54)

A number of experimenters have verified Bert's conclusions that even while breathing excessive quantities of oxygen life cannot be maintained much beyond 35,000 feet altitude Recently L Hill (33) has observed that even while breathing 100 percent oxygen loss of consciousness occurs in men and monkeys when the barometric pressure falls to approximately 115 mm Hg or 45,000 feet Marked motor incoordination as judged by handwriting tests and general physiological and psychological deterioration begins in the neighborhood of 35 000 to 40,000 feet

In order to keep a person in an environment similar to that at sea level while in flight at high altitude, as far as oxygen is concerned one need only increase the percentage of oxygen

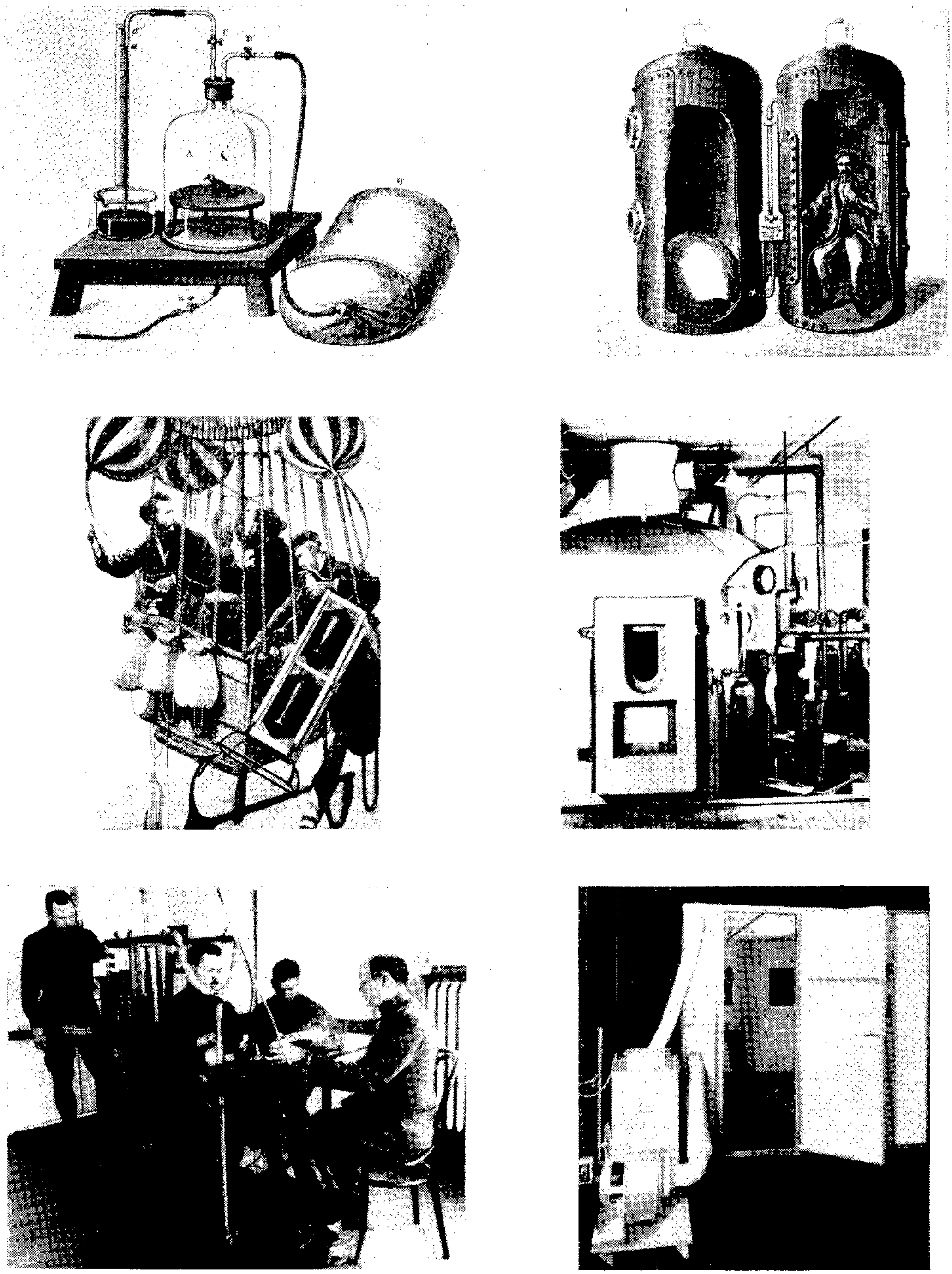

Figure 4.—Experimental procedures for studying effects of high altitude.

in the inspired air, for the partial pressure of oxygen is correspondingly increased. In other words, to maintain a partial pressure of oxygen in the inspired air equivalent to 159 mm. Hg at the various altitudes, the percentage of oxygen should be increased in the proportions indicated in Table 3 and Figures 5 and 7. In practice, while in flight at high altitude, these percentages should be greatly increased since no allowance for ventilation and wastage has been made

TABLE 3

Altitude in relation to barometric pressure and percentage of O_2 needed to maintain 159 mm Hg in the inspired air

Altitude (in feet)	Barometric pressure (mm Hg)	O_2 percent needed
0	760	21 0
10,000	530	30 2
15 000	440	36 4
20 000	375	42 7
25 000	315	50 8
30,000	260	61 6
35 000	220	72 8

It is on this principle that the various types of oxygen-supply apparatus used in altitude flights are constructed By decreasing the percentage of oxygen (barometric pressure being unchanged) the partial pressure of oxygen is decreased This is the method employed in the rebreather or altitude classification test at sea level On the contrary, by increasing the percentage of oxygen in the inspired air, the partial pressure is increased At 40,000 feet, for example, the barometric pressure is 148 mm Hg and the partial pressure of the oxygen of the atmospheric air is 32 mm Hg—too low, of course, to sustain life If by the use of an oxygen-supply apparatus the percentage of oxygen in the inspired air is increased from 21 percent to approximately 80 percent, then the partial pressure of the oxygen of the inspired air would be $0\,80 \times 148$, or 118 4 mm Hg, a pressure capable of sustaining life indefinitely

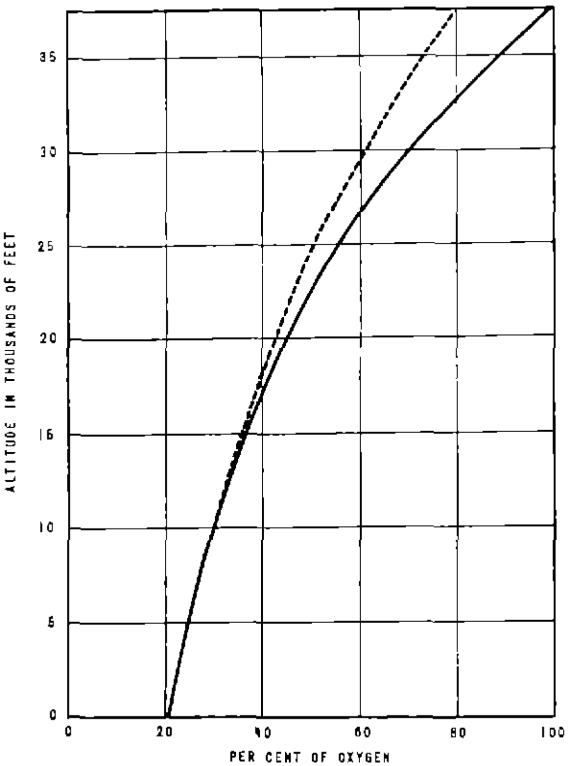

Figure 5—Percent oxygen required at the various altitudes to maintain 159 mm. Hg (Beyne and Clarke)

III Description of the Various Methods Used in Studying the Effects of Oxygen Want (Anoxia)[2]

A great deal of the confusion which exists relative to the effects of oxygen deprivation is probably due to the interpretation of data obtained with different experimental procedures The results may vary, therefore, not because of the different effects of the oxygen want produced by reducing the total pressure as contrasted with the partial pressure, but due to differences in the length of exposure, i e, whether the various mechanisms of acclimatization have had a chance to take place Also, in experiments of short duration the subject may be able to compensate by exerting greater effort Before attempting to state the extent to which data obtained by the various methods are comparable, a brief description of the essential features of each will be discussed

1 *Mountain expeditions*—The most satisfactory way of studying the effects of oxygen want over any extended period of time is to arrange to live at high altitudes in mountainous regions, as in the Alps or the Andes Provided exposure to cold, excessive fatigue from climbing, etc, can be controlled, the mechanisms of acclimatization relating to the decreased oxygen pressure can be observed with great precision Following the initial period of mountain sickness one becomes adjusted to the lack of oxygen and remains fairly comfortable while at rest The highest altitudes to which man can become permanently acclimatized appear to be in the neighborhood of 18,00 feet as observed in

[2] The word anoxia is preferable to anoxemia because the latter term refers to oxygen lack in the blood alone (52)

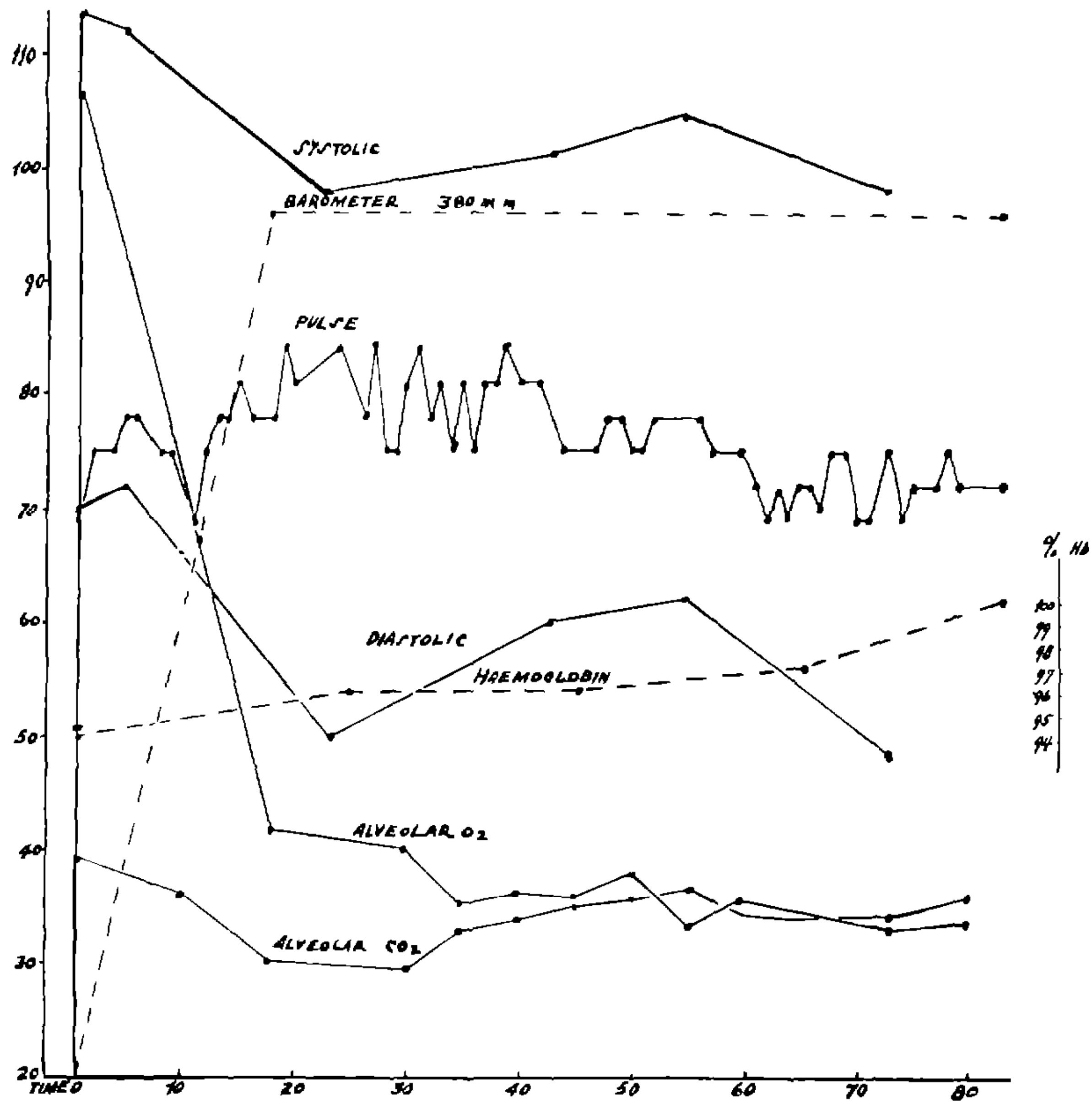

Figure 6—Altitude tolerance test in low-pressure chamber (Air Service Medical)

the mining communities of South America (44)

2 *The low-pressure chamber*—In the low-pressure chamber both the pressure of the air and the concentration of oxygen can be altered so that the atmospheric conditions existing at high altitude can be simulated precisely at sea level By means of a vacuum pump, the *total* pressure can be reduced corresponding to the precise atmospheric conditions at high altitude If the percentage of oxygen is kept constant, the *amount of oxygen available for the organism* will decrease in the same fashion as in an aeroplane climb A valve system automatically regulates air intake and admits a stream of fresh air to the chamber In simulating ascent the air is pumped out faster than it is allowed to enter, and in simulating descent, the pump is turned off and air is admitted at any desired rate Any altitude may be maintained as long

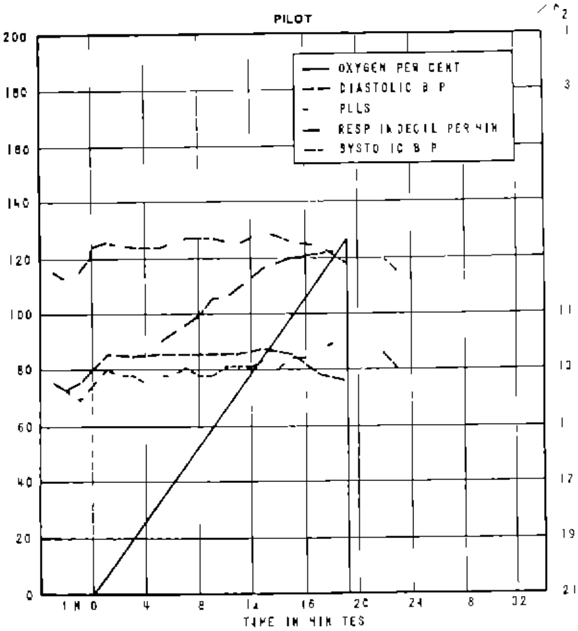

Figure 7—Rebreathing experiment on pilot out of training (Air Service Medical)

as desired From the point of view of reproducing precisely the atmospheric conditions encountered during an aeroplane ascent, this procedure probably is the most satisfactory These chambers are not simple to operate efficiently, particularly if it is desired to regulate not only the ventilation but temperature and humidity also One of the low-pressure chambers used in testing pilots for altitude tolerance during the World War at Mineola, Long Island, is shown in Figure 4 The results of a typical experiment in this chamber at 18 000 feet are shown in Figure 6 Cf Air Service Medical (65)

3 *The low-oxygen chamber*—In low-oxygen chambers the supply of oxygen, or the partial pressure, is diminished by diluting air with nitrogen, leaving the total pressure the same as in the normal atmosphere at sea level The oxygen pressure can be reduced at the desired rate by running in nitrogen from a cylinder through a flow meter simulating the reduction in oxygen pressure during a flight to high altitude A motor blower unit may be used to circulate the air The temperature and humidity may be controlled by blowing the contents of the chamber over ice so as to cool and dry the air, or preferably an air-conditioning unit may be installed so as to control automatically these variables The accumulation of carbon dioxide is prevented by placing soda lime in the air circuit A low-oxygen chamber simplified in design and operation by Barach (4) is shown in Figure 4 This type of chamber is frequently used in clinical medicine in syndromes involving anoxia such as pneumonia, emphysema or cardiac disorders The percent of oxygen in the inspired air is increased from 21 to 40–50 percent They are easy to operate, and are quite spacious and comfortable for experimental purposes The expense is considerable, however, due to the supplies of nitrogen and oxygen which are necessary to maintain the desired experimental conditions In this experiment, most of the tests were carried out in a chamber similar to the one shown in Figure 4

4 *The rebreathing apparatus*—This method involves the use of a rebreathing machine such as the one devised by Henderson and Pierce (1) for testing the tolerance of aviators for high altitude flying during the World War A photograph of this apparatus is shown in Figure 4 With this procedure the subject breathes over and over again the same air with the carbon dioxide absorbed by soda lime The oxygen is gradually absorbed by the subject, and it is thereby reduced from 21 to 6 or 7 percent The average subject usually reaches the limit of his capacity to withstand the effects of oxygen deprivation in 20 to 25 minutes The time at which various changes occur in respiration, pulse, and blood pressure is noted The results from two typical experiments with this apparatus are shown in Figure 7 (subject in poor physical condition) and Figure 8 (subject exceptionally fit) By analyzing the air in the tank at the end of the run, the altitude which the subject is supposedly able to stand is determined A series of psychological tests given during the experiment on the rebreather involve (1) choice reaction times to a series of lights, (2) control of the speed of a motor with the foot from auditory cues, and (3) the regulation of an ammeter from visual cues Since all three of these tests are applied throughout the ex-

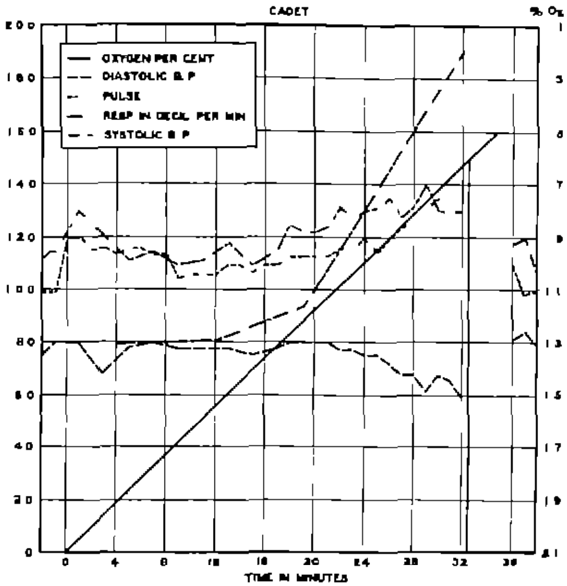

Figure 8.—Rebreathing experiment on exceptionally fit pilot (Air Service Medical)

periment, signs of deterioration usually show up in one or more of the tests. The chief criticism of this procedure is that the experiment takes place too rapidly, and the subject, by exerting great effort, may be able to withstand the effects of the acute oxygen want for short periods of time until the final stages of deterioration. These experiments probably were successful in eliminating physically unfit pilots, but a false impression was given as to the altitudes at which aviators could remain for any length of time and maintain their physical and mental capacities. Flack (19) devised a somewhat similar apparatus for testing pilots in the Royal Air Force. This same principle of gradually absorbing the oxygen available and thus constantly reducing its percentage is widely used in physiological research on specialized aspects of anoxia. The hindrance involved to the subject from the rebreathing apparatus, mouthpiece, etc., is disadvantageous for experiments involving psychological tests. More recently, Christensen and Krogh (15) have recommended for testing pilots the use of a rebreather of 200 liters' capacity and containing 13 percent oxygen at the beginning of the experiment. Since it takes 7 or 8 minutes to lower the oxygen percentage by 1 percent with this procedure, from 30 to 40 minutes elapse before the oxygen is reduced to 7.6 percent, where collapse may be anticipated in the average subject. The reduction of oxygen pressure is, therefore, more gradual, making it possible to observe the reactions of the subjects over longer periods of time.

5. *The Douglas bag procedure* is a fairly satisfactory method for studying specialized aspects of anoxia during short durations in the laboratory. The oxygen concentration can be determined for any desired percentage by running compressed air and nitrogen into the bag through a gas meter. If a 1,000 liter Douglas breathing bag is used, the supply may be sufficient to last for two hours with the concentration remaining the same throughout the experiment. The subject, with the nose clipped, breathes the oxygen mixtures from the bag into the room through a mouthpiece. It is difficult, however, to simulate the gradual reduction of oxygen pressure experienced during flights to high altitude by this method, and the mouthpiece tends to distract the inexperienced subject in taking psychological tests.

6. *Flights to high altitude by aeroplane or balloon.*—The early balloon ascents by the meteorologist, Glaisher (25), and the balloonist Coxwell (1862), and the French scientists Crocé-Spinelli, Sivel and Tissandier (1875), friends of Paul Bert, first called attention to the striking symptoms of diminished oxygen pressure on the human mind and body (Figure 4). Although their accounts of the effects of altitude were based on subjective reports, subsequent research under more controlled conditions has verified their general observations relating to sensory and mental impairment. This method is obviously impractical for scientific research relating to the human problems of modern air transportation.

The most direct attack upon the physiological and psychological effects of altitude in commercial air transportation would be to carry out experiments under actual flight conditions. By such a procedure the conditions could be controlled relating to rate of ascent, height attained, length of exposure, etc. The chief obstacle to such experiments, if they were to be carried out with large numbers of subjects over prolonged periods of time, would be the expense of maintaining and operating one of the most recent and best equipped planes used in commercial aviation If planes of the most recent design and construction were not used, the vibration noise, lack of space and other distractions possibly would give rise to as much impairment in the psychological and certain of the physiological measurements at moderate altitudes as would the lowered oxygen pressure Chamber studies at sea level are desirable if one wishes to separate the relative effects of oxygen deprivation from the effects of many of the other variables of flying such as vibration emotional excitement, sudden movements of the plane, etc Experiments at sea level, however, cannot be entirely substituted for ones under actual flying conditions at high altitude It is important to determine, for example, among many other things, whether the emotional excitement and various mechanisms of acclimatization tend to facilitate or handicap the average person's reaction to diminished oxygen pressure while in flight

IV Are the Results From These Various Methods Comparable?

In attempting to analyze the effects of oxygen want on passengers while in flight on commercial air transport planes, it is important to determine how much of the experimentation can be carried out in low oxygen and low pressure chambers at sea level and how much must be carried out while in the air The following tentative conclusions based upon the data thus far available may be stated

1 The original contention of Paul Bert, verified by such authorities as Haldane (28A), Barcroft (2A), Y Henderson (32), Schneider (65) and more recently, by an extensive series of experiments in Germany (11), appears to be well founded, namely that the important effects of high altitude result from the diminished partial pressure of oxygen If one is interested primarily in the effects of diminished oxygen pressure at high altitude for a given altitude rate of ascent and length of exposure, the essential conditions can be reproduced by reducing the total (barometric) pressure (pressure chamber) or by reducing the partial pressure or percentage of oxygen by diluting air with nitrogen (low oxygen chamber and Douglas bag)

2 The psychological effects i e, sensory, motor and mental deterioration, have been practically the same with all of the methods mentioned above when rate of ascent and length of exposure have been held constant This also assumes that the subjects have not been seriously impeded by face masks, mouthpieces, etc The results of the rebreathing experiments during the World War are not comparable and imply a false (too high) ceiling, since the subject tended to overcome the effects of oxygen want for short periods of time by exerting greater effort The data from chamber studies are more comparable since adequate controls can be run and the subject is unhampered by mouthpieces, etc

3 A number of authors have suggested recently that there are certain differences in the physiological responses to changes in the total pressure (low pressure chamber) as contrasted with the partial pressure (low oxygen or nitrogen dilution experiments) Kaiser (36) believes that under the latter conditions (a) the circulatory responses are different, (b) one does not build up a tolerance for anoxia by repeated exposures (c) the after-effects are more serious, lasting for a number of days or weeks, (d) the loss of consciousness precedes severe cramps, while during a change in total pressure the reverse order follows, and (e) in calculating the partial pressure of oxygen and corresponding altitudes that a subject can tolerate, the altitudes are at least two kilometers higher than that which actually can be reached at high altitude It should be kept in mind that Kaiser's experiments were carried out at the extremes or critical levels of oxygen want These differences, if true, are probably of less significance at more moderate altitudes, i e, 8,000 to 18,000 feet

Another physiological difference in the response to a decreased barometric pressure which might not be present in nitrogen-dilution experiments has been brought forward by Mateeff (43) He has suggested that the decrease in barometric pressure tends to expand the entire vascular bed, thereby reducing the pressure on the circulatory system If the vascular system within the abdominal cavity expands owing to the general elasticity of the area, part of the effective pressure in the heart will be lost to other more rigidly confined vascular areas, the brain particularly suffering by the disturbed distribution of blood Since the circulatory responses to moderate altitudes are not extreme, this can hardly be of great significance during short exposures of several hours' duration Furthermore, the vascular area is filled with a liquid that cannot expand at a constant pressure, hence, there could be no change in the vascular area without a change in volume of the circulating blood This has not been demonstrated in man, except possibly after long acclimatization The expansion of gases in the abdomen and the possible impairment of the digestive processes under conditions of low barometric pressure as contrasted to changes in partial pressure alone may be of some significance, especially if gas-forming foods have been ingested previous to the experiments

It is also possible that the changes in intercranial pressure are different under lowered barometric pressure as contrasted with nitrogen-dilution experiments Armstrong, for example (personal communication), has reported marked changes in intracranial pressure in goats under lowered barometric pressure at very high altitudes The needle was placed in the cisterna magna The alterations were first observable around 16,000 feet, while the increase was 400 percent at 25,000 feet The administration of 100 percent oxygen had no effect in decreasing the pressure However, it is not desirable to make direct applications from the results obtained on animal subjects to human subjects Also, it is well known from the studies of Schmidt (58, 59), Lennox (39), Gibbs (23), and others (24) (16) that oxygen want under any condition gives rise to cerebral vasodilatation and increased blood flow, which could cause an increase in intracranial pressure In general although certain physiological differences may occur in experiments involving changes in the total pressure as contrasted with those of nitrogen dilution alone, the differences appear to be of minor significance at moderate altitudes

4. The most important variable which appears to have given rise to markedly different reactions at similar reduced oxygen pressures relates to rate of ascent and length of exposure, or the length of time during which the oxygen pressure has been lowered and maintained at a constant level As indicated above, the rebreathing experiments during the World War gave rise to the impression that altitudes of approximately 18,000 feet could be tolerated without oxygen because no serious impairment was manifested in many of the subjects until just previous to collapse at very high altitudes The results from chamber studies over longer periods of time, where the subjects are unaware of the changes in the oxygen pressure and do not compensate by exerting greater effort, have indicated considerably lower altitudes in order to remain within margins of safety

Marked differences also appear to be present in comparing the effects of altitude when attained by flight in an aeroplane as contrasted with a motor car or railroad train The winding railroad track or motor road of the average mountain route, as contrasted with the aeroplane in smooth air (also the absence of continual disturbances of the visual fields), may partially account for the fact that one rarely sees typical mountain sickness in an aeroplane at altitudes where it may be first observed on mountain railways

To the question, Can the data obtained at sea level be applied to the effects encountered while in flight at high altitude?, it may be answered that the results obtained thus far seem to indicate that for corresponding rates of ascent and lengths of exposure the physiological and psychological effects are quite comparable, whether the oxygen deprivation is brought about by reducing the total pressure or by nitrogen dilution In fact, as indicated above, there are certain advantages to be obtained from chamber studies at sea level, in that the effects of oxygen want alone can be separated from the effects of vibration, noise, emotional excitement, and rough air However experiments at sea level cannot be entirely substituted for those carried out while in the air because some subjects may improve due to acclimatization while others may deteriorate due to the emotional response to the more realistic setting

V Important Variables of High Altitude in Aviation

The response of the average passenger on a commercial air transport plane to the lowered oxygen pressure encountered while in flight may be influenced by a large number of important variables Since these various factors are of such great importance in understanding the physiological and psychological changes associated with successful acclimatization, a number of the more important ones are listed below In the experiment which will be reported later, the rate of ascent in relation to the altitudes where the effects are first manifested and where the effects appear to become marked (i e, between 10 000 feet and 20 000 feet) has been studied in a large group of subjects varying in age and physical fitness

1 *Height attained* —At what altitude is the average passenger first affected physiologically and psychologically? Where are the effects marked and at what altitude are the effects dangerous?

2 *Rate of ascent*—What rate of ascent is most advantageous so that mechanisms of acclimatization can be brought into action in the average passenger? For example, is it possible to take passengers to 12,000 feet in 1 hour and 15 minutes without serious distress, while in 15 minutes serious impairment is manifested? What are the effects of sudden loss of pressure or a very rapid rate of descent, other than on the middle ear?

3 *Length of exposure* —At what altitude can one become comfortably acclimatized so that no ill effects are manifested following the exposure, and at what altitude does definite deterioration set in after a certain number of hours, even though an initial adaptation appears to be taking place? For example, even though the average passenger is able to adjust to 10,000 feet or 12,000 feet for 3 to 4 hours, does he show definite ill effects after 6 to 8 hours?

4 *Amount of physical exertion* —At what altitude does a stewardess, a pilot or a cameraman manifest symptoms of anoxemia, as contrasted to the passenger who sits quietly during a flight?

5 *Roughness of the air and movements of the plane* —In what way or ways does rough air accentuate the effects of lowered oxygen pressure, or does 'airsickness' become more acute when combined with the effects of anoxia at high altitude?

6 *The physical characteristics of the individual* —Since one of the most striking features of the response of a group of passengers to high altitude is the great diversity of reactions, what are the most significant factors? In a group of 200 subjects for example, several may collapse at 10,000 or 12,000 feet, while others may not collapse until 24,000 feet is reached What sort of distribution curve could be constructed so as to establish safe altitudes of operation for the entire flying population? A number of important variables which relate to the physical characteristics of the individual in responding to high altitude appear to be

(a) Age—chronological age contrasted with physiological age,

(b) Tolerance due to repeated flights,

(c) Amount of regular exercise each day or week,

(d) Degree of fatigue previous to flight,

(e) Number of hours of sleep the previous night,

(f) The kinds of food ingested,

(g) The amount of alcohol or narcotics previous to the flight,

(h) Emotional adaptation, freedom from worry, mental conflicts etc ,

(i) Degree of relaxation or the reverse, i e muscular tension

(j) Clinical anomalies, such as cardiac disorder, anemia, asthma, malaria, metabolic disturbances, tuberculosis, etc

VI The Physiological Responses of the Organism to Lack of Oxygen and Excess Carbon Dioxide

There is no storage of oxygen in the body, unlike many other chemical substances necessary to maintain life, such as carbohydrate In emergencies of oxygen want, the release of red cells (oxygen carriers) by the spleen and bone marrow may be considered as a storehouse in a limited sense. In man the blood is really the only storehouse for oxygen, and its capacity is very limited. Hence the body lives a hand-to-mouth existence with respect to its oxygen supply. When the available supply of oxygen is shut off, there is loss of consciousness within a minute or two. Many physiologists estimate that the deterioration of the cortical tissue due to oxygen lack is so profound that recovery is impossible after 5 to 8 minutes. The lower centers of the brain and the spinal cord may survive after one-half hour or more of oxygen deprivation. The efficiency of one's body is dependent upon the constancy of the internal environment, i. e., the regulation of temperature, water, oxygen, the hydrogen-ion concentration, etc. Since man's higher nervous faculties developed due to the constancy of these organic processes, an extreme variation in any one of them, particularly the oxygen percentage, will produce striking effects on the nervous system and other tissues of the body. The seat of oxidation is the living cell and the quantity of oxygen taken up by the cells is conditioned primarily by the degree of activity of the organism.

The use of breathing, of course, is to obtain supplies of oxygen for the tissues and to get rid of the carbon dioxide, thereby maintaining the proper balance of gases in the blood. The air in the alveoli is brought into proximity with the lung capillaries, thus providing for the exchange of gases between the blood and the air. There is a reduction of oxygen in the alveoli (lungs) to an average of 14 percent, due to dilution by the residual air in the lungs. The average composition of carbon dioxide in the alveoli is 5.5 percent. The venous blood which comes to the lungs gives off carbon dioxide and takes up oxygen until it comes into equilibrium with the air of the alveoli. On account of the pressure of oxygen in the alveoli being greater than that in the blood, oxygen is absorbed into the blood by diffusion. Slight alterations in the alveolar carbon dioxide pressure cause great changes in breathing. In the case of exercise, for example, more oxygen is absorbed by the tissues and a greater amount of carbon dioxide is given off. Increased breathing takes place immediately so as to wash out the excess carbon dioxide and restore the equilibrium. Table 4 shows the average amount of carbon dioxide produced per person during the various conditions of activity (69).

TABLE 4

Condition	CO_2 in cubic centimeters per minute (0° C. and 760 mm. Hg)	Condition	CO_2 in cubic centimeters per minute (0° C. and 760 mm. Hg)
Rest—in bed	0.197	Walking—4 m. p. h.	1.40
Rest—standing	264	Walking—5 m. p. h.	2.39
Walking—2 m. p. h.	662	Heavy labor	4.78
Walking—3 m. p. h.	922		

During vigorous exercise the demand for extra oxygen by the tissues is met by a number of important physiological changes, the chief ones being: (1) a very great increase in lung ventilation; (2) a large increase in the output of the heart per minute; (3) a rise in the arterial pressure so that the blood flows in greater volume per minute through the expanded capillaries of the region where activity requires a greater oxygen supply; (4) heightened rate of diffusion or exchange of gases in the capillaries of the lungs and of the contracting muscles; and (5) a slight increase in number of the red corpuscles. Thus the rate of breathing will vary (1) in proportion to the degree of activity of the body, i. e., the metabolic rate, and (2) with the reaction of the blood, i. e., so as to maintain the appropriate oxygen tension in the blood.

Breathing appears to be controlled automatically by the respiratory center, a small area located in the medulla oblongata at the base of the brain. If this center is destroyed, all rhythmical respiratory movements cease, or, if these cells are totally deprived of oxygen within 8 to 10 minutes, the destructive changes are so great that they do not recover. The intimate connection between the nervous and chemical control of breathing is shown by the activity of the respiratory center, since its functioning depends, among other things, upon the composition of the gases in the blood circulating through it[3] During anoxia with a decreased percentage of available oxygen or during exercise with an increased percentage of carbon dioxide, the arterial blood visits, among other places, the respiratory center, the carotid sinus and carotid body (It has been shown that the carotid body is especially sensitive to asphyxial or anoxemic blood[4]) The excess carbon dioxide acts as a stimulus, and the cells discharge more nerve impulses to the muscles of respiration so that their action is more vigorous Thus the increased ventilation of the lungs pumps out the extra carbon dioxide until the proper balance is again reached The heart rate, which also increases, exposes the blood more often in a given length of time to the alveolar air Thus more oxygen is supplied to the deficiency of the respiratory, cardiac, and vasomotor centers of the medulla (69)

The extraordinary sensitiveness of the respiratory center can be demonstrated by the fact that an increase of only 0 22 percent carbon dioxide in the alveolar air will cause the ventilation of the lungs to be increased 100 percent Excess carbon dioxide in the inspired air beyond the normal 0 04 percent has noticeable effects since the rise in alveolar carbon dioxide hinders elimination of the excess carbon dioxide There is increased breathing with full and rapid pulse with 4 percent carbon dioxide, and compensation is still more difficult with a further rise, at 6 percent, headache and mental confusion develop Toxic effects appear with higher percentages the heart slows consciousness is lost, the breathing becomes feeble and finally ceases Experimental work indicates that the variations in ordinary breathing are due to an increased production of carbon dioxide For example, when the carbon dioxide percentage of the inspired air was increased the lung ventilation increased as is shown in Table 5 (69)

TABLE 5

Percent CO_2	Average respiratory volume (liters)	Percent of increase in lung ventilation
0 03	6 3	
1 00	8 3	32 0
2 00	11 3	79 5
4 00	19 4	207 9
6 00	32 7	418 6
8 00	46 6	639 0

The amount of oxygen which can be carried by the blood is dependent upon the quantity of hemoglobin located in the red cells In its ordinary form, *oxyhemoglobin* is a bright red color and contains oxygen which it readily parts with in the tissues It then becomes reduced hemoglobin, which is of a purplish color and which in turn absorbs oxygen from the air in the alveoli The arterial blood in normal subjects at sea level contains from 94 to 96 percent of its hemoglobin in the oxygenated form and only 4 to 6 percent in the reduced form[5]

The amount of oxygen taken up by the blood depends upon the partial pressure of oxygen in the alveolar air, the temperature of the blood, the concentration of salts in the blood, and the hydrogen-ion concentration of salts in the blood (carbon dioxide tension) During rest the whole blood volume passes through the lungs about once per minute, and it may pass as often as ten times during exercise When the arterial blood is imperfectly saturated the condition which develops is called *anoxemia* It is indicated by the bluish color of the skin and lips (*cyanosis*)

VII The Physical and Psychological Responses of the Organism While in Flight at High Altitude

The most important physiological changes associated with the diminished barometric pressure at high altitude (Figure 9) are as follows (a) stimulation of the respiratory center and an increase in the pulmonary ventilation, (b) a decrease in the alveolar oxygen and carbon dioxide tensions (Figure 9, also Figure 10 from Haldane (28A) and Figure 11 from Schneider (65)) (c) dilatation of the alveoli favoring a more efficient respiratory exchange (d) an in-

[3] For an authoritative account of the regulation of respiration by the blood gases cf L J Henderson Blood A Study in General Physiology Yale University Press New Haven 1928 and R Gesell The Chemical Regulation of Respiration Physiol Rev 5 551 1925

[4] Heymans C Bouckaert J J et Regniers P Le Sinus carotidien Doin Paris, 1933

[5] For authoritative discussions of hemoglobin and oxygen in relation to high altitude cf Peters J P and Van Slyke D D Quantitative Clinical Chemistry (Chapter 12) Williams & Wilkins Baltimore 1931 and Dill D B Life, Heat and Altitude Harvard University Press Cambridge 1938

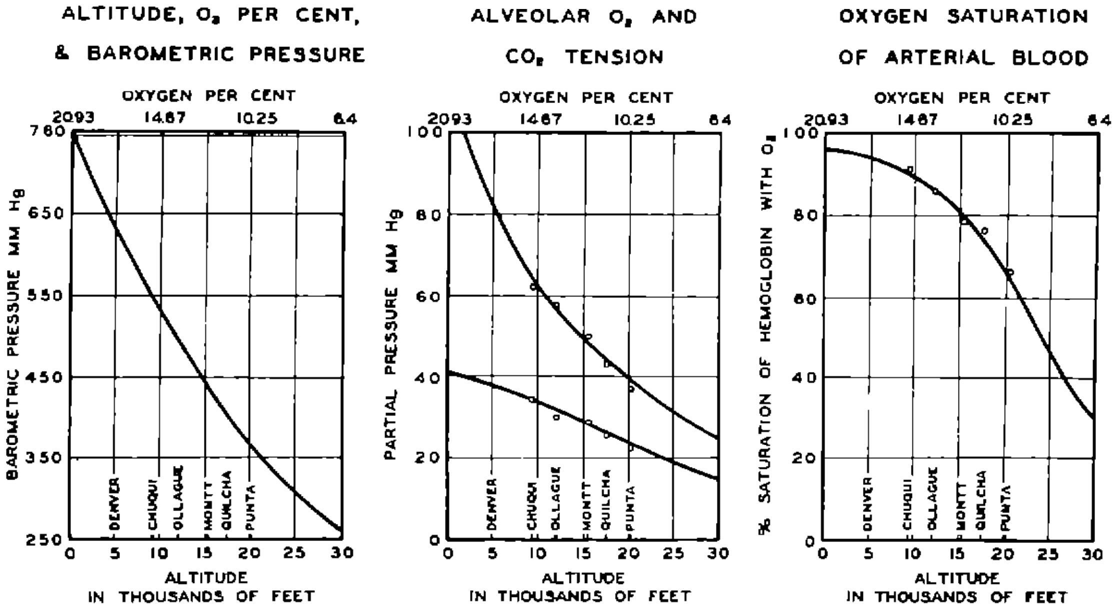

Figure 9 —Barometric pressure in relation to alveolar O_2 and CO_2 and oxygen saturation of arterial blood (Chilean Expedition, 1935)

tial increase in the heart rate and blood pressure and an increase in cardiac output, followed by a gradual return to normal while at rest, (e) an increase in the amount of hemoglobin in the circulation (cf Figure 12 from Haldane (28A)), (f) a decrease in the arterial oxygen saturation associated with the fall in alveolar oxygen tension (Figure 9), and (g) changes in the acid-base equilibrium—the initial effect being one of alkalosis associated with the excess elimination of carbon dioxide Sudden and extreme anoxemia depresses the activity of the respiratory center so that a delayed effect may be the retention of carbon dioxide and consequently an acid reaction in the blood (cf McFarland (44))

The psychological changes follow closely the rapidity and severity of the physiological alterations in the organism If anoxemia is produced suddenly, as during an aeroplane ascent, the most striking effects are on the central nervous system The psychological impairment is insidious and often completely unobserved subjectively When the barometric pressure is reduced one-third, i e, to 480 mm Hg, at approximately 12 500 feet, the psychological changes are objectively measurable by tests (45) A review of the literature indicates that the average unacclimatized subject during short exposures manifests only slight impairment at 12,000 feet and deteriorates rapidly at 15.000 to 16,000 feet In a recent high-altitude expedition to the Andes, significant psychological changes in acclimatized subjects were not observed until 15,500 and 17,500 feet altitude (44), where the oxygen saturation of the arterial blood in ten subjects averaged 80 percent and 76 percent, respectively (cf Figure 9) (17)

Previous studies dealing with the effects of high altitude while in flight have been chiefly concerned with the physiological changes during rapid ascents, i e within fifteen to twenty minutes, to critical altitudes varying from 15,000 to 25,000 feet Schneider and Clarke (56) made observations on the changes in the alveolar oxygen and carbon dioxide during rapid ascents to 15,000 feet Schnell (57), Beyne (7), Fronius (21), and Schubert (60) have carried out experiments dealing primarily with the circulation, respiration, alveolar air, and metabolism during aeroplane ascents within one-half an hour to 18,000 to 20,000 feet On trans-Andean flights of approximately one-half hour's duration to 14,000 and 16,500 feet,

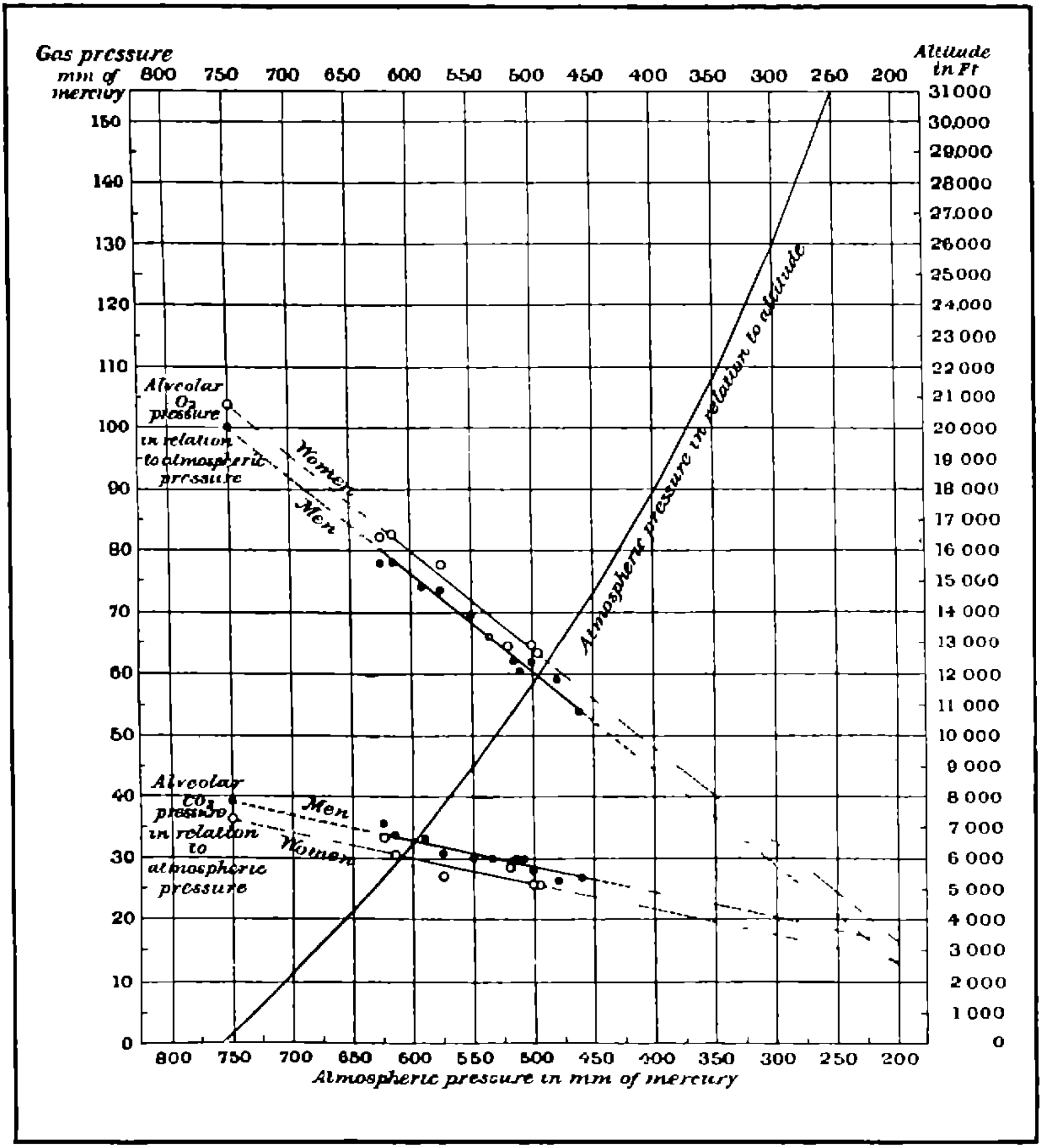

Figure 10—Atmospheric pressure in relation to alveolar O_2 and CO_2 (Haldane)

McFarland (44) made observations of the sensory and mental functions as well as the alveolar air and circulation These authors all emphasize the psychic nervous involvement and the impairment of sensory functions above 14 000 to 16,000 feet In rapid ascents as high as 26,500 feet with pilots, Baertschi (5) observed that feelings of euphoria were noticeable up to 16 500 feet Beyond that height weakness and apathy were noticeable, and, in

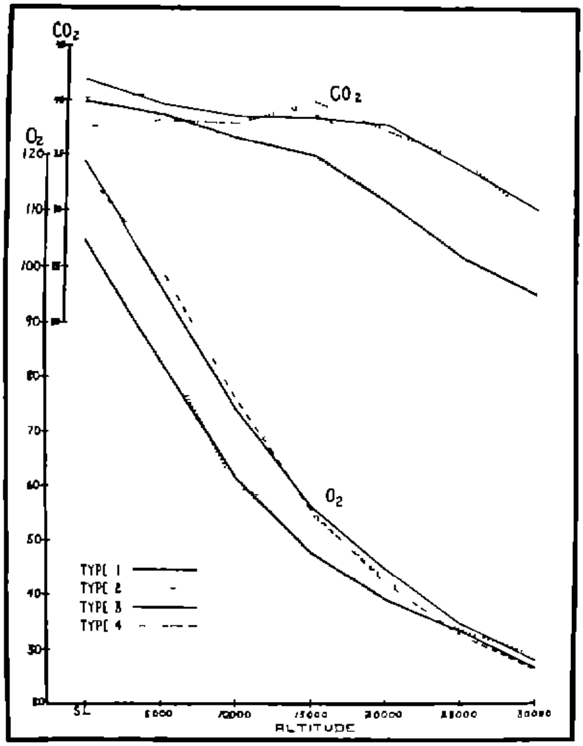

Figure 11.—Average alveolar CO_2 and O_2 tensions at simulated altitudes (Schneider et al.)

addition, there were disturbances of attention, of volition, and of the special senses, accompanied by marked sleepiness and fatigability.

A number of experiments on airmen have indicated that repeated flights to high altitude facilitate acclimatization as manifested by a greater acceleration in the pulmonary ventilation (20), and increase in the red cells and hemoglobin (37), and a higher alveolar oxygen partial pressure. Fronius (21) found that daily flights have the same effect as a prolonged stay in the mountains and that progressively higher altitudes could be tolerated. In comparing a group of pilots who could tolerate very high altitudes with those who could not, Christensen and Krogh (15) found that the good ones showed a greater pulmonary ventilation, a distinctly lower partial pressure of carbon dioxide, and a higher partial pressure of oxygen. Thus there is some evidence that pilots become partially acclimatized through repeated flights to high altitude, particularly those who show an

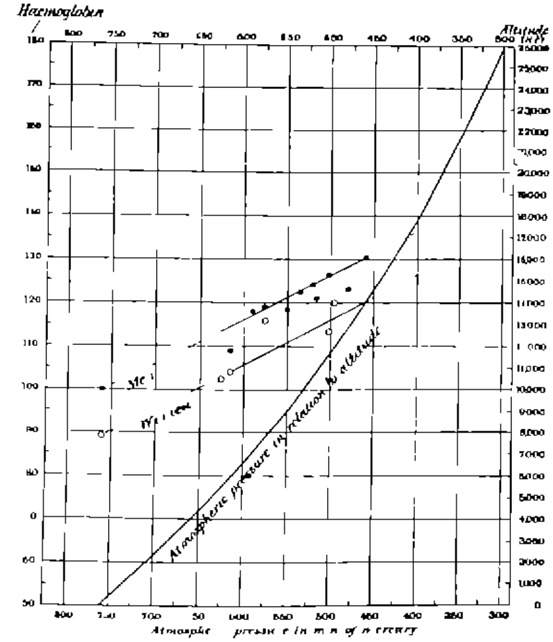

Figure 12.—Average hemoglobin percentages in persons living permanently at different altitudes (FitzGerald)

initial favorable response. No extensive studies have been made of the effects of high altitude on large numbers of passengers at comparable altitudes to those attained in commercial air transportation.

Part II.—EXPERIMENTAL STUDIES

I. Statement of Problem

As indicated previously, this report attempts to analyze the effects of flying at high altitude on the average unacclimatized passenger under present flight conditions on commercial air transport planes. Interest has centered in studying large groups of subjects, varying in physical fitness and in age (from 18 to 72 years) at different rates of ascent and lengths of exposure to altitudes of 10,000 to 18,000 feet. An attempt has been made, therefore, to determine the altitudes where the physiological effects are extensive enough to bring about an impairment in the average passenger's psychological reactions and feeling of well-being, as well as the altitudes which appear to be definitely dangerous. In addition, an attempt has been made to determine the importance of rate of ascent relative to the specific altitudes studied For example is the average person significantly impaired at 10,000 or 12,000 feet? If he is affected psychologically or in terms of discomfort by a rapid ascent to 12 000 feet in 15 minutes, will he be able to make a better adjustment, i e, remain mentally alert and comfortable, if that altitude is attained during 1 hour and 15 minutes? Are 2 or 3 hours at 12,000 to 14,000 feet positively dangerous to the average passenger's general physical well-being after that altitude has been once attained?

II General Outline of the Investigation

The entire research program may be divided into six parts and the various experiments will be discussed in the following order Parts I to IV, inclusive were sponsored by the Bureau of Air Commerce

1 This experiment was carried out in the Applied Laboratory of the Department of Psychology at Columbia University Over 200 subjects were studied at various simulated altitudes and at two rates of ascent as shown in Table 7 in a low-oxygen chamber The tests included continuous records of pulse and blood pressure, alveolar oxygen and carbon dioxides, and a series of six psychological tests involving motor sensory, and mental functions

2 The second part of the investigation was concerned with the problem of age in relation to ability to tolerate oxygen deprivation or altitude There were three groups of subjects divided into the following age groups 17–30 years 30–45 years, and 45–72 years In this study the tests mentioned in Part I above were given following a rapid ascent to a simulated altitude of 14 000 feet in the low-oxygen chamber at Columbia University

3 The third aspect of the study was concerned with the question of physical fitness in relation to ability to tolerate high altitude In this part of the investigation a group of Columbia college students in good physical condition were compared with those in poor health but without definite organic illness The testing procedure was similar to the one described above In addition, 30 control or "normal" subjects and 35 psychoneurotic patients from Vanderbilt Clinic without organic illness but with objective signs of "chronic exhaustion and fatigue" were tested twice, once under control conditions, i e, normal air, and once following a rapid ascent to a simulated altitude of 18,000 feet in the low-oxygen chamber at Columbia University In this part of the investigation samples of blood were taken at the beginning and at the end of each session in addition to the Schneider Index and psychological tests

4 In cooperation with the late H T Edwards of the Harvard Fatigue Laboratory, a series of tests were made on four subjects in the low-oxygen chamber at Columbia University, with and without 3 0 percent carbon dioxide in the inspired air A series of physiological and psychological tests, as well as analyses of the blood gases, were made on each subject in an attempt to determine the value of excess carbon dioxide in counteracting the effects of the oxygen want encountered at high altitude

5 In cooperation with Dr D B Dill and Mr H T Edwards a number of experiments were carried out during the past year in the low-oxygen room at the Harvard Fatigue Laboratory, Boston, and in the low-pressure chamber at Wright Field, Dayton, Ohio The results of these studies, especially the psychological data will be reviewed briefly so as to compare the data obtained at similar altitudes under different experimental procedures of reducing the oxygen pressure The studies will be reported separately by Dr D B Dill et al since they were sponsored by the Fatigue Laboratory independent of the grant from the Bureau of Air Commerce The purpose of these experiments was to test the effects of more prolonged exposures to simulated altitudes of 14,000 and 17,000 feet over a six-hour period with a normal amount of carbon dioxide and with the addition of 3 percent carbon dioxide in the inspired air

6 During the summer months an opportunity was afforded through the cooperation of United Air Lines and Pan American Airways to carry out a number of studies during transcontinental flights, as well as during the more prolonged flights of the trans-Pacific opera-

tions These investigations have been reported separately but will be briefly referred to here so as to compare the data obtained under actual flight conditions with those collected under simulated altitudes in low-oxygen and low-pressure chambers at sea level The essential information relating to these various parts of the investigation, such as number of subjects, altitude, rates of ascent, etc , has been summarized in Table 7

III **Experimental Procedure**

In the major experiment (Part I) a large number of subjects were studied at six different altitudes from 10 000 to 18,000 feet at two rates of ascent—rapid (15 to 30 minutes) and slow (45 minutes to 1 hour and 30 minutes) The rapid ascents averaged between 600 and 700 feet per minute, and the slow ascents less than one-half as fast The altitudes and the time required to simulate these ascents are shown in Tables 6 and 7, and also graphically in Figure 13 Once the simulated altitude was reached the various tests were given twice during the two hours at the altitudes indicated The length of each experiment varied from 3½ to 4½ hours, depending on the rate of ascent Over 250 experiments were carried out in the main part of the study In a number of cases two subjects were studied at the same time, however, for the most part the subjects were tested in the chamber individually Two experimenters inside the chamber gave the tests, and one outside the chamber made frequent analyses on the Haldane apparatus of the percentages of oxygen and carbon dioxide in the chamber

TABLE 6

TIME REQUIRED FOR RAPID AND SLOW ASCENTS AT ALTITUDES INDICATED

[Length of stay—two hours Data taken as of control, first and second hour]

Altitude (feet)	Time in minutes	Altitude (feet)	Time in minutes
10 000 Rapid	15	16,000 Rapid	30
10,000 Slow	40	16,000 Slow	75
12,000 Rapid	20	18,000 Rapid	30
12,000 Slow	45	18 000 Slow	90
14,000 Rapid	20	21,000 Rapid	35
14 000 Slow	45		

The subjects came to the laboratory at least 1½ to 2 hours following a meal both in the mornings and afternoons In the series where blood samples were collected, the subjects came

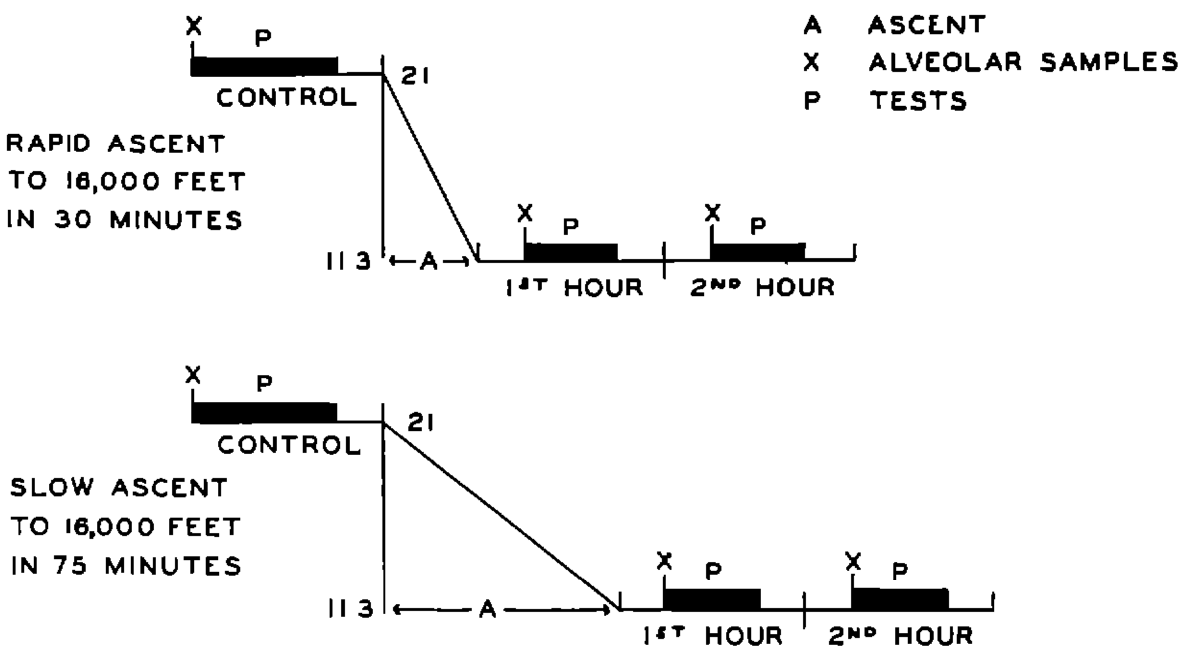

Figure 13—Diagram of experimental procedure (McFarland)

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to the laboratory in the morning under basal conditions Each subject was given the various tests a day or so previous to the experimental series so as to become acquainted with the procedures, and also to attempt to overcome the effects of practice in the psychological tests After the subject entered the chamber a complete series of tests was taken before the ascent Then the various tests were repeated twice, as indicated in Figure 13

TABLE 7

NUMBER OF SUBJECTS IN THE VARIOUS EXPERIMENTS AT THE ALTITUDE AND RATES OF ASCENT INDICATED

Experiment	Altitude	Percent oxygen	Number of subjects: Rapid ascent	Number of subjects: Slow ascent
Part I Major Experiment on Effects of Altitude	(1) 10 000 feet	14 25	18	14
	(2) 12 000 feet	13 20	14	12
	(3) 14 000 feet	12 20	20	13
	(4) 16 000 feet	11 25	27	19
	(5) 18,000 feet	10 35	30	13
	(6) 21,000 feet	9 15	12	
Part II Age in Relation to Altitude	(1) 14 000 feet	12 20		
	(a) 17 to 30 years	12 20	[1] 20	13
	(b) 30 to 45 years	12 20	15	
	(c) 45 to 72 years	12 20	16	
Part III A Rate of Ascent and Altitude in Relation to Physical Fitness	(1) 16 000 feet	11 25	10	
	(2) 16 000 feet	11 25		10
	(3) 12 000 feet	13 20	16	
B Psychoneurotic Group	(1) 18 000 feet	10 35	35	
C Control Group (same as Part I)	(1) 18 000 feet	10 35	[1] 30	
Part IV and Part V Low Oxygen (11% O_2) Experiments with and without Excess Carbon Dioxide (3 0% CO_2)	(1) 18,000 feet	10 35		
(a) Columbia Experiment	17–22,000 feet		4	
(b) Harvard Experiment	17 000 feet		4	
(c) Wright Field (Low Pressure Chamber) Experiment	17–22 000 feet		4	
Part VI Experiments while in Flight on Commercial Air Transports				
(a) Transcontinental Flights	6–12 000 feet		6	
(b) Trans Pacific Flights	8–12 000 feet			11
Total number of subjects			256	108

[1] Same group of subjects as in Part I not included in total

The tests were given in a Barach portable oxygen chamber (7 x 8 x 8 feet), where the gases, temperature, ventilation, and humidity could be regulated (4) The concentration of oxygen was maintained at the desired percentage by running in nitrogen[6] The carbon dioxide never exceeded 0 7 percent Samples of the gas mixtures were taken inside the chamber at the time the alveolar air was taken, also, a sample was taken by an assistant from the outside of the chamber The analyses were made with a Haldane gas-analysis apparatus These determinations were made at the beginning and end of each period when the percentage of oxygen was altered The ventilation was provided by a motor blower unit The air current was passed through a tank which contained ice to cool and dry the air The temperature was maintained between 68–74° F, and the humidity between 40–50 percent The chamber was in a part of the laboratory free from distractions and other outside influences The experimenter was protected against the effects of anoxia by breathing additional amounts of oxygen through a nasal catheter The small change in percentage of oxygen was compensated for by a small amount of nitrogen from a cylinder outside the chamber

1 *The subjects* —An attempt was made to get subjects to serve in the experiments who were of the same socio-economic status as the average flying population In the main experiment many of the younger subjects were undergraduate and graduate students in Columbia University Those who were more advanced in age were for the most part professional men in New York City engaged in the practice of law, teaching, or business The total age range was from 17 to 72 years The subjects varied in physical fitness from college athletes to those who led sedentary lives with a very limited amount of exercise There was also a fairly average distribution as to height and weight Those with known organic illness were eliminated from the experiments As a result of the tests, however, a number of the individuals were shown to be in very poor health and were sent to the University Medical Office One of

[6] The altitudes corresponding to the oxygen mixtures in the chamber were determined by data compiled by the U S Bureau of Standards (cf Table 2) which relate altitude barometric pressure and the percentage of oxygen available for the organism at each level The calculations are based upon a constant temperature of 15° C with allowance for the day to-day variations in the barometric pressure

the subjects, for example, collapsed at 9,000 feet after approximately 10 minutes during the ascent About half of the subjects volunteered to serve because of their general interest in aviation The others were paid by the hour for each experiment All of the subjects were males

2 *The physiological and psychological tests*—During each experimental session a series of physiological and psychological tests was given to each subject, as follows

Physiological tests

- *a* *Pulse rate* recorded practically continuously during the ascent and at frequent intervals thereafter
- *b* *Systolic and diastolic blood pressure*—Tycos recording sphygmomanometer
- *c* *Alveolar oxygen and carbon dioxide*—The analyses were run in duplicate on the standard Haldane gas-analysis apparatus

Psychological tests

- *a* *Handwriting*—The subject was asked to copy 8 lines of the Swedish language
- *b* *Heterophoria* test for ocular muscle balance (1)
- *c* *Choice reaction times* (Sillitoe apparatus (61) 50 reactions on a portable reaction time apparatus with five colored lights Time recorded in hundredths of a second.
- *d* *Color naming*—Both time and errors were recorded during the naming of colors (68)
- *e* *Code test*—Cf Johnson and Paschal (34) Recording of the time and errors involved in transliterating 50 letters from a code
- *f* *Memory* (66)—Immediate recall for series of ten four-letter words after exposure for 15 seconds each
- *g* *Record of physiological and psychological complaints*—Each subject kept a running account of his chief symptoms in his own handwriting Also at the end of each experiment the subjects indicated their chief ailments on a standardized test form (cf Table 16)

3 *Biochemical tests* (Parts III, IV, and V)

- *a* Lactic acid (Friedemann, Cotonio and Shaffer)
- *b* Blood sugar (Folin-Wu)
- *c* Inorganic phosphorus (Youngberg)
- *d* Calcium (Clark Collip)
- *e* Creatinine (Folin-Wu)
- *f* Hemoglobin (Newcomer)
- *g* Blood gases, Van Slyke apparatus (Arterial oxygen and carbon dioxide) (52)

4 *Statistical treatment of data.*—The pulse and blood pressure records were taken practically continuously during the ascent and well into the first part of the first experimental hour so as to follow the acclimatization made by the subject Thereafter pulse and blood pressure records were made every 10 to 15 minutes In the final data the pulse and blood pressure records were averaged for successive 5-minute intervals during the ascent and for every 20-minute period during the remaining 2 hours

The alveolar air samples were taken 3 times during each experiment, first under control conditions and again at 15 to 25 minutes of the first and second hours at each altitude A sample of the air in the chamber was also taken at the time the alveolar air was collected Each sample was analyzed in duplicate on the Haldane apparatus

The scores for each subject in the various tests were obtained first under control conditions (air) previous to the ascent and again during each of the two hours following the ascent In Tables 8 to 15 these three scores, Control, First hour, and Second hour, represent the averages for the number of forms or trials on each test for the respective periods

All of the scores for the physiological and psychological tests are grouped according to altitude and rate of ascent Separate groupings have been made for age and physical fitness The final results are recorded in terms of means, variability (standard deviations) and critical ratios (determination of the significance of a difference between means in terms of probability)

These data have been treated by the usual statistical procedures In determining the critical ratios, use was made of Fisher's method for small samples (cf Guilford J P, Psychometric Methods, McGraw-Hill, 1936) The critical ratios are important, since they are measures of the probability that the differences between the sea level and the altitude means are significant i e due to the effects of the diminished oxygen pressure rather than resulting from sampling errors and variability These measures are shown in the tables in terms of chances in 100 that the difference could have arisen by chance It is generally accepted that 5 chances in 100 or less indicates a significant difference and is so used in the results of this study (cf Fisher (18A))

Since the control scores in the various experiments were not identical due to different subjects being used, the changes in the mean scores in the physiological and psychological tests (with the exception of the heterophoria test) are also shown as percent change with the control score being taken as 100 The use of percent change from the control makes direct comparison of results easier and at the same time made it simpler for charting the data

The essential comparisons have been made between the results obtained in the physiological and the psychological tests at sea level and at the respective altitudes after a rapid ascent, using first-hour data only A comparison has also been made for the differential effects of rapid and slow ascents to a particular altitude and finally the differential effect of age and physical fitness at a single altitude following a rapid ascent

IV Results of the Experiments on Large Groups of Subjects (Part I)

1 *The pulse rate* —The alterations in pulse rate per minute for each group (throughout the experimental session) under the various conditions of rate of ascent and altitude attained have been summarized in Table 8 In addition to the means, the standard deviation (index of variability within the group), the significance of the observed differences (whether the difference is due to chance or not), and the index of change (control=100) are shown for the various groups under the conditions as indicated The average increase in pulse rate during rapid ascents appeared to be significant statistically during the first 20 minutes at 12,000 feet, however the mean pulse rate dropped to the control level by the end of the first hour At 14,000 feet and above the mean pulse rate remained significantly higher throughout each experi-

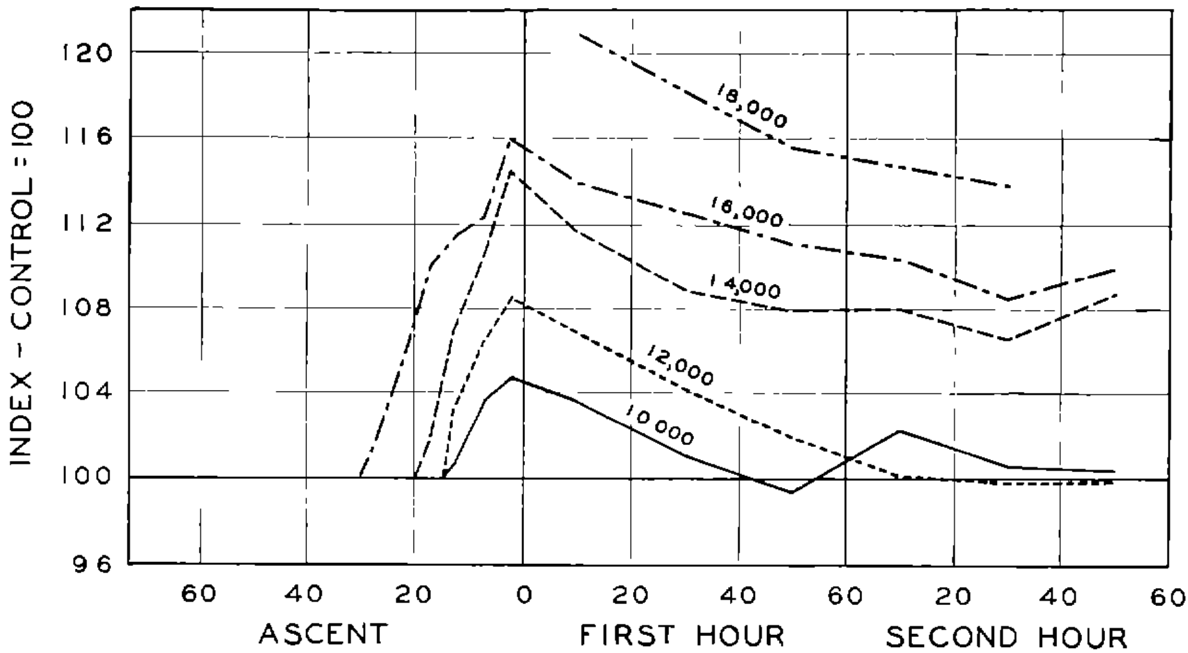


Figure 14 —Pulse rate during rapid ascent and during 2 hours at high altitude (McFarland)

mental period The first significant increase during slow ascents was at 16,000 feet

The extent of the variations in pulse rate during rapid ascents varying from 10,000 to 18,000 feet is shown graphically in Figure 14 in terms of the index of change (control=100) There appears to be a close relationship between increase in pulse rate and height attained A well controlled rise in pulse rate is apparently a favorable response to lowered oxygen pressure

TABLE 8 —**Pulse Rate**

(Altitude in feet)	Control	First hour 1–20 mins	First hour 21–40 mins	First hour 41–60 mins	Second hour 1–20 mins	Second hour 21–40 mins	Second hour 41–60 mins
10,000 rapid							
Mean	74 33	77 00	75 06	73 86	76.00	74.60	74 71
S D	10 03	11 23	12 11	11.79	13 05	10 07	7 56
Significance [1]		5–10	60–70	50–60	100	60–70	70–80
Index of change	100 0	103.6	101 0	99 4	102 2	100 6	100 5
10,000 slow							
Mean	80 33	77 83	74 00	74 67			
S D	8 17	6 22	5 66	5 69			
Significance		20–30	1–2	5–10			
Index of change	100 0	96 9	92 1	92 9			
12 000 rapid							
Mean	78 36	83.60	81 62	79 46	78 55	77 36	78.09
S D	9 42	9 90	10 80	9 67	14.27	12.81	15 55
Significance		0–1	30–40	50–60	90–100	70–80	80–90
Index of change	100 0	106.8	104.2	102 0	100 2	98.7	99 6
12,000 slow							
Mean	76.38	77 89	81 57	76 17			
S D	6.60	6.99	10 58	7 16			
Significance		50–60	10–20	70–80			
Index of change	100 0	102.0	105 5	99 7			
14 000 rapid (17–30 yrs)							
Mean	77 27	86.21	83 96	83 36	83 49	82.34	83 91
S D	9 50	8.85	9 38	10 40	9 29	9 70	9 62
Significance		0–1	0–1	0–1	0–1	1–2	0–1
Index of change	100 0	111 6	108.7	107 9	108.0	106 6	108 6
14,000 slow							
Mean	74.17	75 67	74 50	75 00			
S D	14.11	11 47	12 54				
Significance		70–80	90–100	70–80			
Index of change	100 0	102.0	100 4	101 1			
16,000 rapid							
Mean	75 5	86 0	84 9	83 8	83 3	81 8	82 9
S D	9 22	13 23	12 96	12 80	11 83	11 13	12 41
Significance		0–1	0–1	0–1	0–1	0–1	1–2
Index of change	100 0	113.9	112 5	111 0	110 3	108 4	109 8
16 000 slow							
Mean	78 50	85 05	83 17	83 67	84.61	84.67	84 40
S D	10 78	10 77	14 29	10 85	12 47	12 92	12 10
Significance		1–2	10–20	2–5	2–5	5–10	10–20
Index of change	100 0	108.4	105 9	106 6	107 8	107 9	107 5
18 000 rapid							
Mean	70 20	84.80		81 20		79 96	
S D	6 62	9 65		8 48		8.92	
Significance		0–1		0–1		0–1	
Index of change	100.0	120 8		115 6		113 8	
21,000 rapid							
Mean	67 80		94 30			96 50	
S D							
Significance			0–1			0–1	
Index of change	100 0		139 1			142 3	
14 000 rapid (30–45 yrs)							
Mean	81 50	85 00	84.00	79 89	78.00	79 00	80 00
S D	8.56	13 00	10 52	9 77			
Significance		60–70	90–100	40–50			
Index of change	100 0	104.3	103.1	98 0	95 7	96 9	98 2
14 000 rapid (46 yrs and over)							
Mean	74 33	76 58	74.75	72.27	72.33	73.93	73.80
S D	13 62	14 96	14 07	12.99	10 25	11 99	10 04
Significance		70–80	80–90	80–90	80–90	90–100	90–100
Index of change	100 0	103 0	100 6	97 2	97 3	99 3	99 3

[1] Chances in 100 that the difference from the control could have arisen by chance Five chances in 100 or less are necessary before the significance of the difference is reasonably certain, or before chance can be reasonably ruled out

in the average person in good health. Many of the subjects in poor physical condition responded with extreme variations in pulse rate, i. e., either an unusually large increase in rate, a sudden decrease in rate, or no change at all. There is a general tendency for the pulse rate to return to more normal levels at the lower altitudes (10–12,000 feet) provided the subject acclimatizes fairly well and remains at rest. At the higher altitudes, however, this does not occur (cf. Figure 14).

In comparing the alterations in pulse rate during rapid and slow ascents, i. e., attaining the simulated altitudes within 15 to 30 minutes as contrasted with 1 hour and 15 minutes to 1 hour and 30 minutes, the variations appear to be less extreme if the organism has a longer time to become acclimatized. This tendency is shown graphically in Figure 16 for 16,000 feet altitude. In fact a number of the subjects who were able to become acclimatized to 16,000 feet following a slow ascent collapsed upon reaching similar altitudes after a rapid ascent. On the average, the group differences in pulse rate were not significant at 10,000 and 12,000 feet when the rapid and slow ascents were contrasted. (Cf. Table 8.)

2. *The systolic and diastolic blood pressure.*—The mean variations in systolic and diastolic blood pressure under the different conditions of reduced oxygen pressure are shown in Tables 9 and 10. These results are partially shown in graphic form in Figures 17 and 18 in terms of the percent change from the control.

On the average the blood pressure records do not show very definite trends. This is primarily due to the fact that the increases and decreases tend to cancel out, thereby indicating only small changes in the group means. During the rapid ascents the variations both in systolic and diastolic pressure were less extreme than during the slow ascents. (Cf. Figures 17 and 18.) At moderate altitudes most subjects react with an initial increase in either the systolic or diastolic blood pressure, or both, followed by a well controlled fall to normal values.

In contrasting the rapid and slow ascents to 16,000 feet, both the initial increase and prolonged effects in the systolic and diastolic pressures were higher during and following the rapid ascents.

3. *The alveolar oxygen and carbon dioxide.*—The average partial pressure of oxygen and

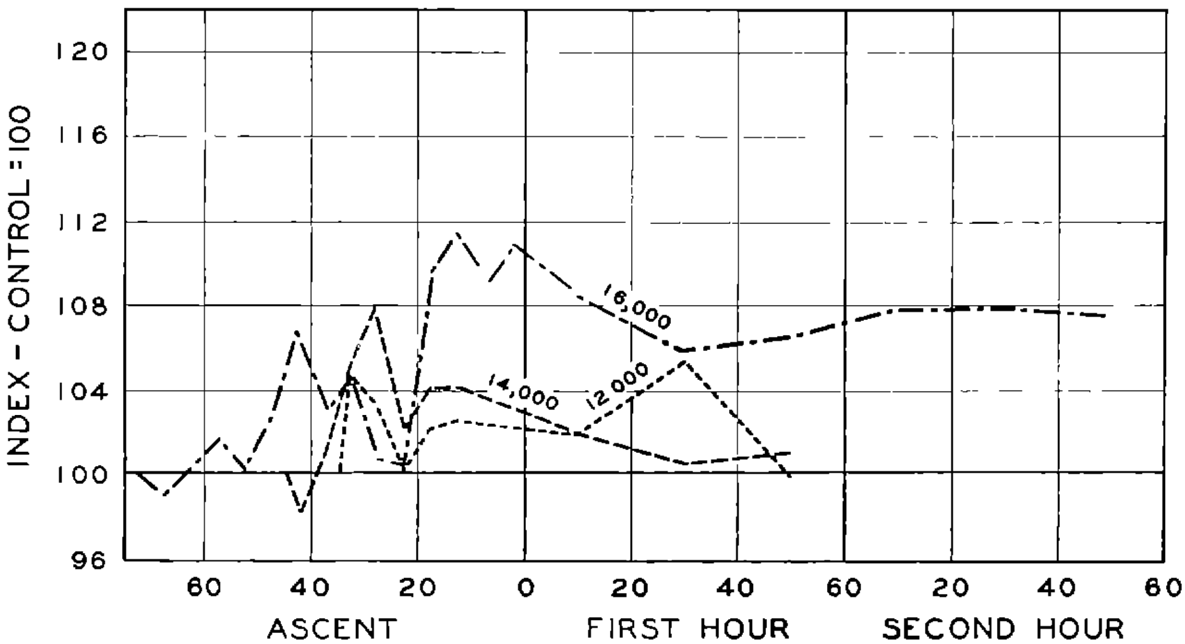


Figure 15.—Pulse rate during slow ascent and during 2 hours at high altitude (McFarland)

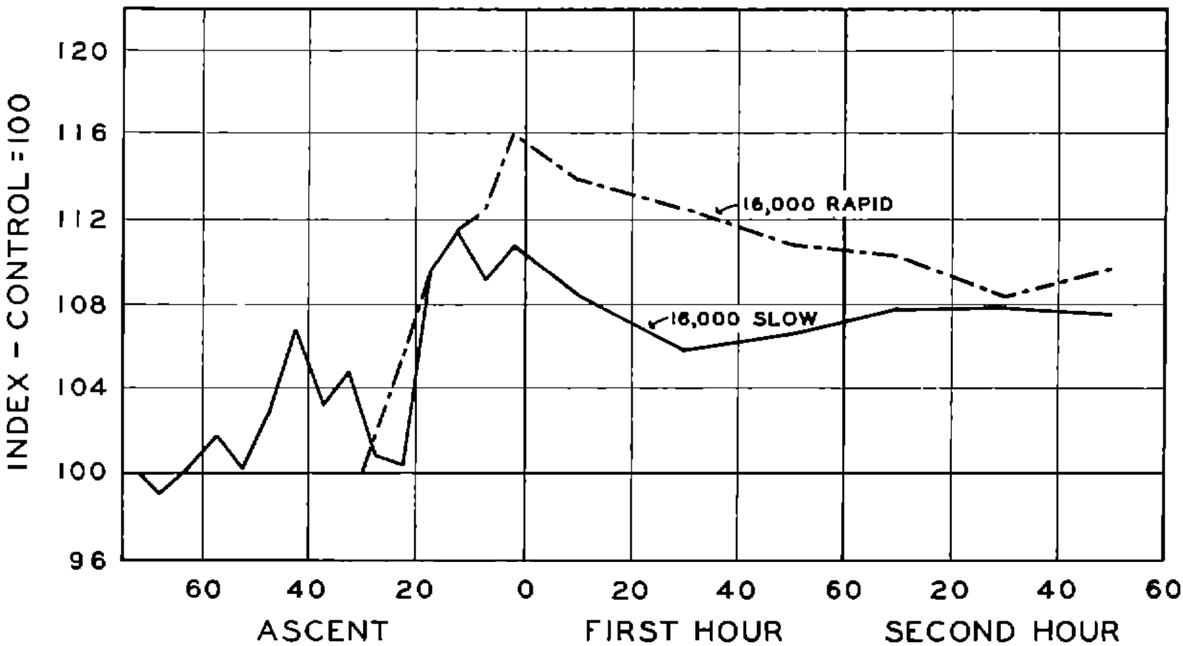


Figure 16 —Pulse rate during rapid and slow ascents and during 2 hours at 16,000 feet (McFarland)

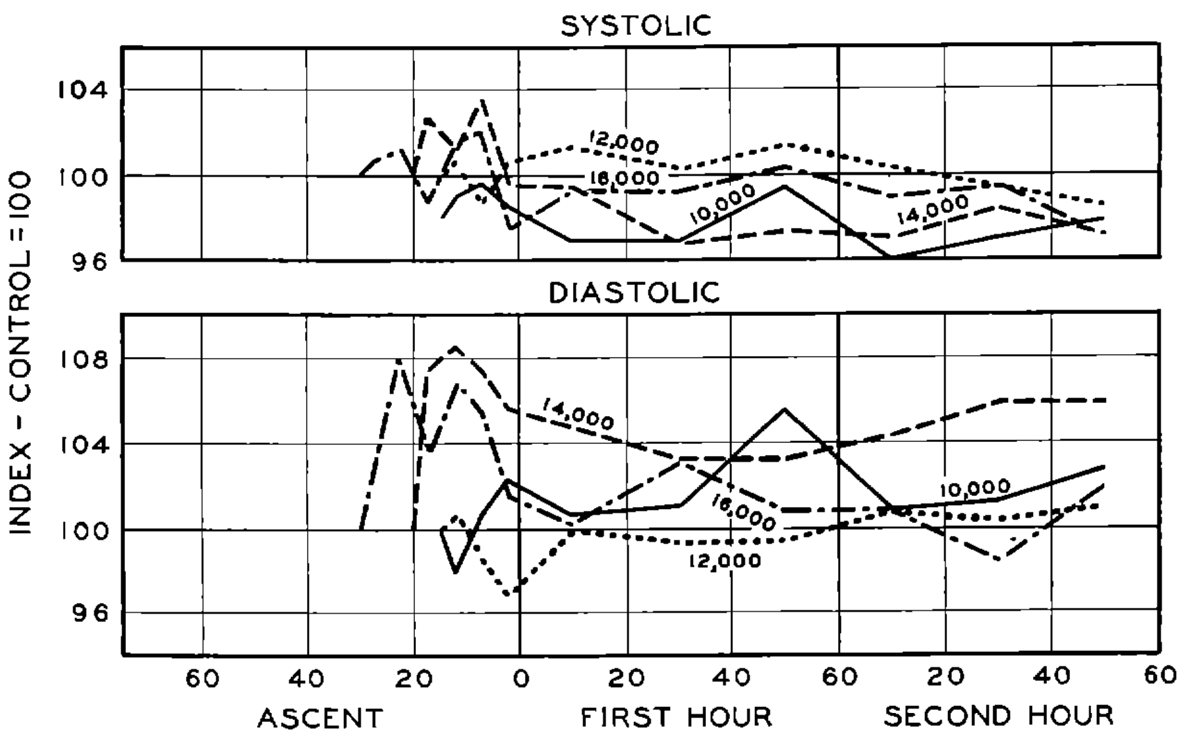


Figure 17 —Blood pressure during rapid ascent and during 2 hours at altitudes indicated (McFarland)

carbon dioxide in the alveolar air in relation to the percentage of oxygen and carbon dioxide in the chamber is shown in Table 11 and Figure 19 for the various groups under the conditions of diminished oxygen tension as indicated.

The results indicate that, on the average, the partial pressure of oxygen is significantly higher and the carbon dioxide lower in acclimatized subjects compared to unacclimatized ones. (Cf. Figure 19 for results from the Chilean Expedition (10 men) after several months at the various stations as indicated.) In contrasting the

TABLE 9.—Systolic Blood Pressure

(Altitude in feet)	Control	First hour 1–20	First hour 21–40	First hour 41–60	Second hour 1–20	Second hour 21–40	Second hour 41–60
10 000 rapid							
Mean	113.17	109.83	109.83	112.89	108.80	109.90	111.00
S. D.	9.20	10.10	9.77	9.80	9.02	8.02	7.18
Significance[1]		2–5	10–20	30–40	5–10	20–30	30–40
Index of change	100.0	96.9	96.9	99.4	95.8	97.0	97.9
10 000 slow							
Mean	111.83	109.67	109.83	111.00			
S. D.	7.72	9.18	9.03	6.06			
Significance		20–30	10–20	10–20			
Index of change	100.0	95.5	95.6	96.6			
12 000 rapid							
Mean	110.29	111.62	110.69	111.92	110.64	109.55	107.40
S. D.	6.83	9.49	9.80	9.07	7.23	12.63	5.80
Significance		50–60	80–90	60–70	40–50	70–80	60–70
Index of change	100.0	101.2	100.3	101.5	[illegible]	99.3	97.3
12 000 slow							
Mean	107.13	107.86	102.71	103.96			
S. D.	4.43	4.28	7.82	8.89			
Significance		70–80	40–50	40–50			
Index of change	100.0	100.7	95.8	97.0			
14 000 rapid (17–30 yrs.)							
Mean	112.77	112.13	109.05	109.71	109.51	111.41	109.65
S. D.	12.71	14.01	11.23	14.28	14.84	14.09	15.65
Significance		60–70	1–2	5–10	2–5	2–5	5–10
Index of change	100.0	99.4	96.7	97.3	97.1	98.4	97.2
14 000 rapid (30–45 yrs.)							
Mean	120.00	123.38	112.71	115.67	115.67	117.67	119.00
S. D.	13.17	16.84	11.55	12.40			
Significance		60–70	10–20	10–20			
Index of change	100.0	102.6	93.9	96.4	96.4	98.1	99.2
14 000 rapid (45 yrs. and over)							
Mean	130.08	126.27	127.58	128.00	128.67	132.33	134.67
S. D.	22.80	24.22	27.15	25.60	23.47	29.08	25.37
Significance		60–70	40–50	20–30	20–30	70–80	90–100
Index of change	100.0	97.1	98.1	98.4	98.9	101.7	103.6
14 000 slow							
Mean	113.83	111.33	114.33	111.00			
S. D.	3.63	7.14	7.60				
Significance		30–40	90–100	40–50			
Index of change	100.0	99.5	100.4	97.5			
16 000 rapid							
Mean	110.4	109.4	109.4	110.8	109.4	109.8	108.6
S. D.	10.10	7.74	11.40	11.76	12.41	12.04	18.36
Significance		40–50	50–60	80–90	50–60	90–100	70–80
Index of change	100.0	99.1	99.1	100.3	99.1	99.5	98.4
16 000 slow							
Mean	[illegible]	109.33	108.12	106.06	113.28	106.72	109.31
S. D.	12.51	11.68	10.25	8.41	11.25	13.52	12.46
Significance		0–1	1–2	0–1	5–10	1–2	5–10
Index of change	100.0	91.0	94.8	92.1	98.5	92.6	94.9
18 000 rapid							
Mean	108.90	109.12		108.76		109.40	
S. D.	5.83	11.37		10.60		11.02	
Significance		90–100		80–90		90–100	
Index of change	100.0	100.2		100.1		100.5	
21 000 rapid							
Mean	109.5		[illegible]			127.3	
S. D.							
Significance							
Index of change	100.0		111.7			116.3	

[1] Chances in 100 that the difference from the control could have arisen by chance. Five chances in 100 or less are necessary before the significance of the difference is reasonably certain, or before chance can be reasonably ruled out.

two rates of ascents in this experiment the partial pressure of oxygen was significantly higher following the slow ascents compared to the rapid ones

4 *Results of the Psychological Tests*

a Handwriting test—In an attempt to observe the effects of diminished oxygen pressure on motor control in a highly practiced reaction like handwriting, two different tests were used, the first involving the copying of a paragraph of eight lines of Swedish language, and the second a handwritten commentary on the physiological

TABLE 10—**Diastolic Blood Pressure**

(Altitude in feet)	Control	First hour, 1–20	First hour, 21–40	First hour 41–60	Second hour, 1–20	Second hour, 21–40	Second hour 41–60
10,000 rapid							
Mean	65 72	66. 17	66. 44	69 50	66. 30	66. 60	67 57
S D	7 66	6 72	8. 90	9 14	6. 89	7 86	6 22
Significance [1]		80–90	70–80	30–40	80–90	80–90	60–70
Index of change	100 0	100 7	101 1	105. 7	100 9	101. 2	102. 8
10 000 slow							
Mean	61. 67	63 67	66. 17	63. 00			
S D	5. 20	5. 18	5. 03	3 05			
Significance		30–40	20–30	50–60			
Index of change	100 0	103. 2	107 3	102. 2			
12,000 rapid							
Mean	66. 71	66. 69	66. 18	66 36	67 27	66. 91	67 40
S D	6. 97	6 94	5. 19	6. 73	5 67	7 64	3 67
Significance		70–80	100	60–70	70–80	90–100	90–100
Index of change	100 0	100 0	99 3	99 5	100 8	100 3	101. 0
12,000 slow							
Mean	64. 00	62. 00	64 00	62. 71			
S D	6. 47	4. 58	5. 10	5. 04			
Significance		40–50	80–90	30–40			
Index of change	100 0	96. 9	100 0	98. 0			
14,000 rapid (17–30 yrs)							
Mean	63. 69	66. 62	65 84	65. 70	66. 35	67 45	67 35
S D	7 89	8. 78	8 48	9 06	9 59	10. 30	9 73
Significance		2–5	2–5	10–20	5–10	1–2	0–1
Index of change	100. 0	104. 6	103 4	103 2	104. 2	105. 9	105. 8
14,000 rapid (30–45 yrs)							
Mean	73. 80	71 50	69 43	73. 56	75. 33	71 00	73 67
S D	10. 40	11 86	8. 67	10. 83			
Significance		20–30	20–30	50–60			
Index of change	100 0	96. 4	94 1	99 7	102. 1	96. 2	99 8
14,000 rapid (45 yrs and over)							
Mean	80 00	77 83	78. 67	83. 00	84. 33	87 20	97 20
S D	17 84	17 60	18. 50	23. 19	26. 66	34. 49	31 01
Significance		50–60	60–70	60–70	60–70	50–60	30–40
Index of change	100 0	97 3	98. 3	103. 7	105. 4	109 0	121 5
14,000 slow							
Mean	63. 67	66 67	68. 00	66. 00			
S D	5 64	7 80	8 69				
Significance		20–30	10–20	5–10			
Index of change	100 0	104. 7	106. 8	103. 6			
16 000 rapid							
Mean	64. 6	64 8	66 6	65 2	65 2	63 5	65 9
S D	7 28	9 48	8. 86	7 41	9 59	7 93	10 77
Significance		80–90	10–20	70–80	60–70	80–90	50–60
Index of change	100 0	100 8	103 1	100 9	100 9	98. 3	102. 0
16,000 slow							
Mean	67 06	66. 82	67 20	65. 71	67 17	66. 88	69 21
S D	9 59	9 00	7 82	10 10	6. 45	10 36	12. 09
Significance		50–60	40–50	60–70	80–90	60–70	80–90
Index of change	100 0	99 6	100 2	98. 0	100. 2	99 7	103 2
18 000 rapid							
Mean	70 30	63. 12		67 12		07 40	
S D	6. 70	11 65		10 01		9 00	
Significance		0–1		5–10		5–10	
Index of change	100 0	89 8		95. 5		95 9	
21,000 rapid							
Mean	70 00		48. 50			47 50	
S D							
Significance							
Index of change	100 0		69 3			67 9	

[1] Chances in 100 that the difference from the control could have arisen by chance Five chances in 100 or less are necessary before the significance of the difference is reasonably certain, or before chance can be reasonably ruled out

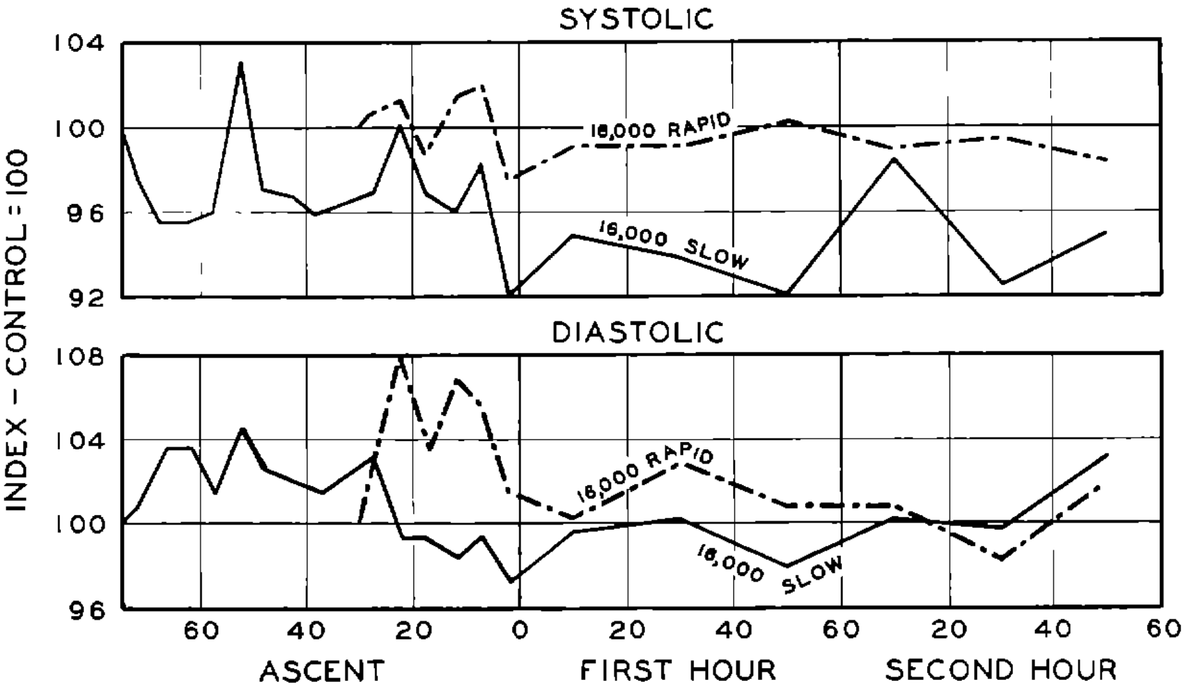


Figure 18a—Blood pressure during rapid and slow ascents (McFarland)

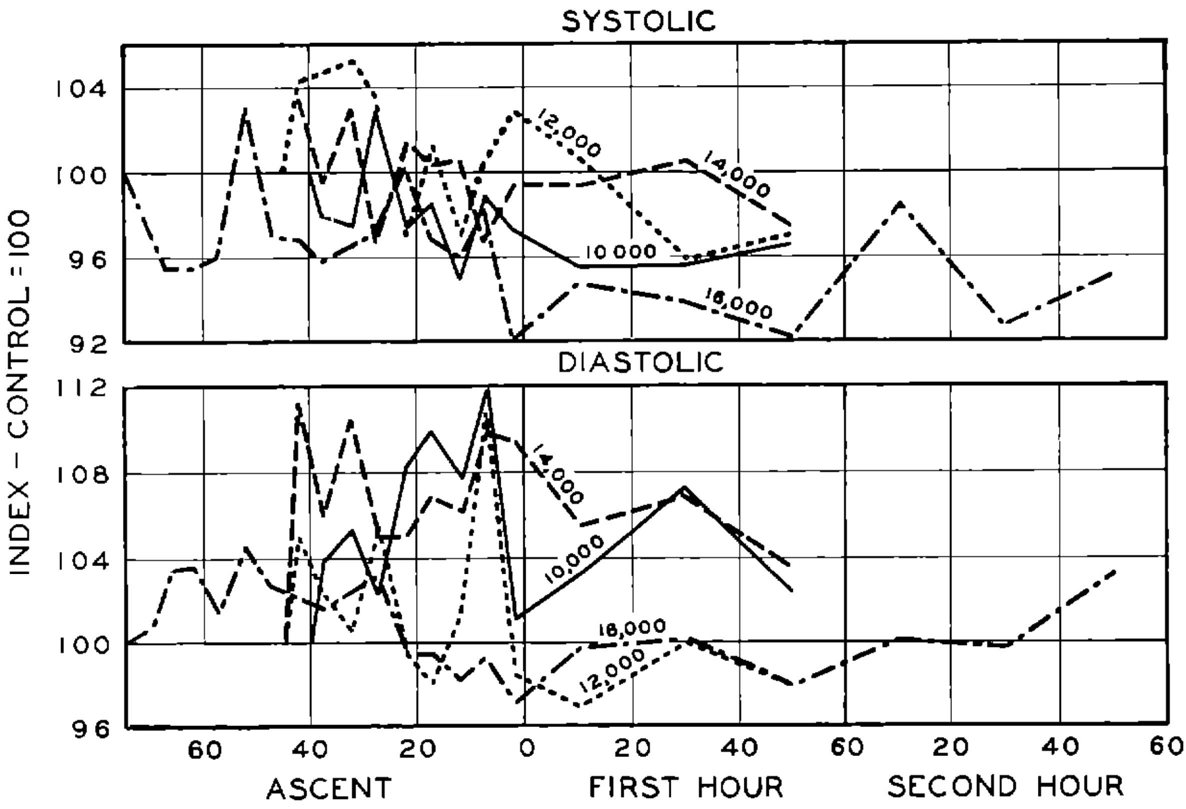


Figure 18b—Blood pressure during slow ascent (McFarland)

TABLE 11 —**Means of Alveolar pCO_2 and pO_2 and Chamber Concentrations for Altitudes Indicated**

(Altitude in feet)	Control		First hour				Second hour			
			pCO_2	pO_2	Chamber		pCO_2	pO_2	Chamber	
	pCO_2	pO_2			$\%CO_2$	$\%O_2$			$\%CO_2$	$\%O_2$
10 000 rapid	40 4	99 0	39 1	54 3	0 36	13 95	44 2	54 8	0 65	14 10
10 000 slow	39 2	103 0	37 6	59 3	43	14.06	–			
12,000 rapid	38 2	105 5	36 1	56 8	36	13 13	34 5	56 5	51	12 94
12,000 slow	40 5	100 1	37 7	53 7	49	13 25	40 3	50 5	72	13 36
14 000 rapid (17–30 yrs)	39 9	98 5	39 4	43 68	38	12 06	37 0	44 4	69	12.20
14 000 rapid (30–45 yrs)	37 5	101 9	35 5	43 2	39	12 04	34 3	45 0	90	12 14
14,000 rapid (45 yrs and over)	38 03	100 3	36 2	47 6	45	12 42	35 5	54 6	63	12.19
14 000 slow	38 8	100 9	38 8	43 9	40	12 16	38 5[1]	38 5[1]	55[1]	12 02[1]
16,000 rapid	38 5	101 1	35 3	38 6	37	11 16	34 9	38 4	63	11 18
16 000 slow	38 5	101 3	34 6	43 2	47	11 10	34 3	39 4	66	11 30

[1] One subject

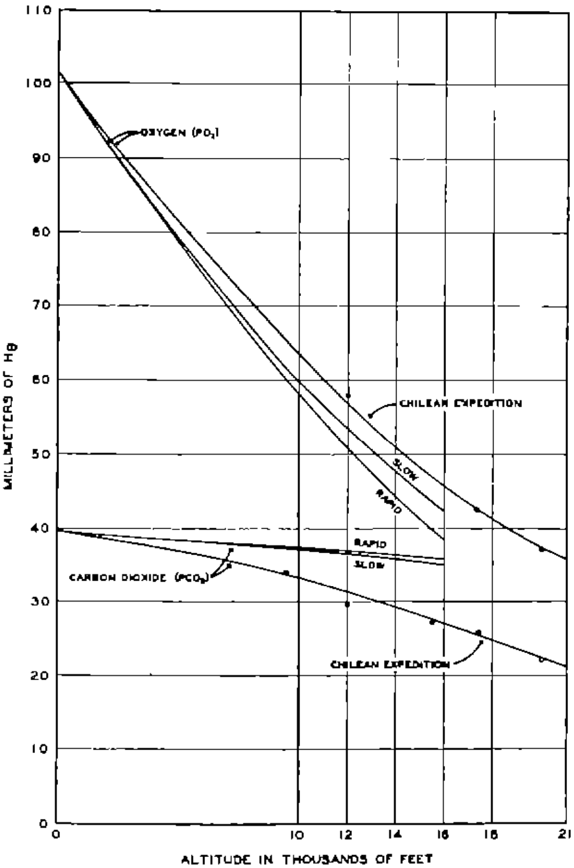


Figure 19 —Alveolar oxygen and carbon-dioxide tension in unacclimatized and acclimatized man (McFarland)

and psychological changes observed during each experiment The samples of handwriting were scored on the basis of changes from the normal handwriting, using the following criteria (1) irregularities in distance and height, i e , size (2) slant of the letters, (3) changes in the slopes of the lines, (4) tremors, (5) omissions of letters and punctuation The scores on these various items were then added into a total score and calculated in terms of the percent change from the control

TABLE 12

PERCENT DEVIATION IN HANDWRITING FROM THE CONTROL (100) FOR THE ALTITUDES AND RATES OF ASCENT INDICATED

	Control	First hour	Second hour
10 000 feet			
Rapid	100	99 0	90 3
Slow	100	99 2	–
12,000 feet			
Rapid	100	96 7	93 8
Slow	100	93 4	–
14,000 feet			
Rapid	100	93 8	92 2
Slow	100	95 0	–
16 000 feet			
Rapid	100	92.0	86 2
Slow	100	92.8	91 0
18,000 feet Rapid	100	76 2	

The results are shown in Table 12 and Figure 20 On the average, there was a significant impairment in this test at 14,000 feet and above the deterioration in motor control being fairly great at 16,000 and 18,000 feet following a rapid ascent

A number of typical specimens of handwriting under control (air) conditions and reduced oxygen tension are shown in Figures 22 to 25 Figures 22 and 23 show reproductions of the Swedish passages which were to be copied, and Figures 24 and 25 the voluntary comments of two of the subjects as to their general acclimatization to the lower oxygen pressure

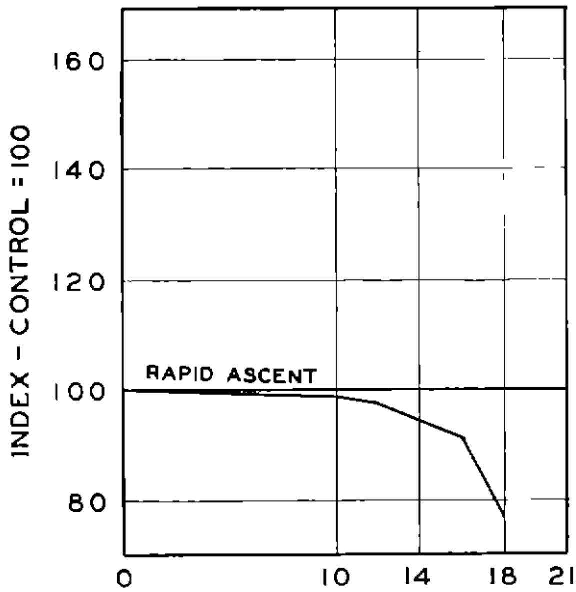


Figure 20 —Handwriting tests (McFarland)

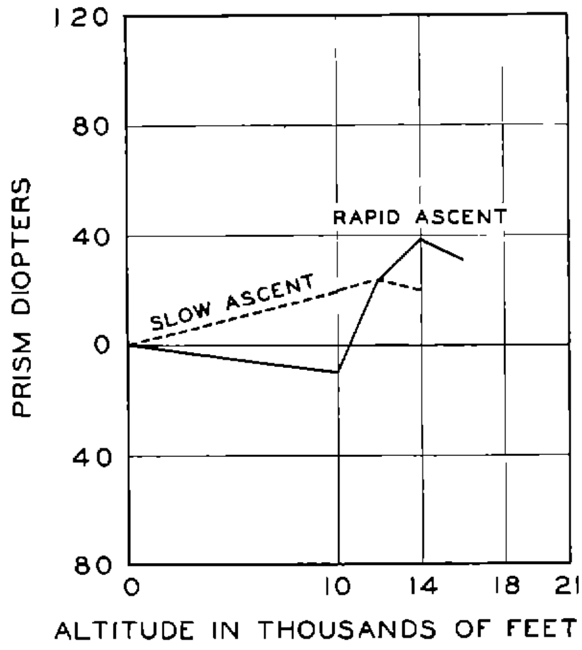


Figure 21 —Heterophoria tests (McFarland)

b Heterophoria test —In this test the amount of ocular muscle unbalance was measured under constant lighting conditions with a pair of 5-diopter prisms at 40 cms distance The results, as shown in Table 15 and Figure 21, indicate the mean deviation in prism diopters from the control value (not orthophoria) under the various conditions of diminished oxygen pressure The significance of the observed differences was not reliable statistically until the oxygen partial pressure was reduced corresponding to altitudes of 14,000 feet and above

c Choice reaction times —The results of this test under the various conditions of oxygen deprivation are shown graphically in Figure 26 in terms of percent change from normal—100 The reaction times, as measured in hun-

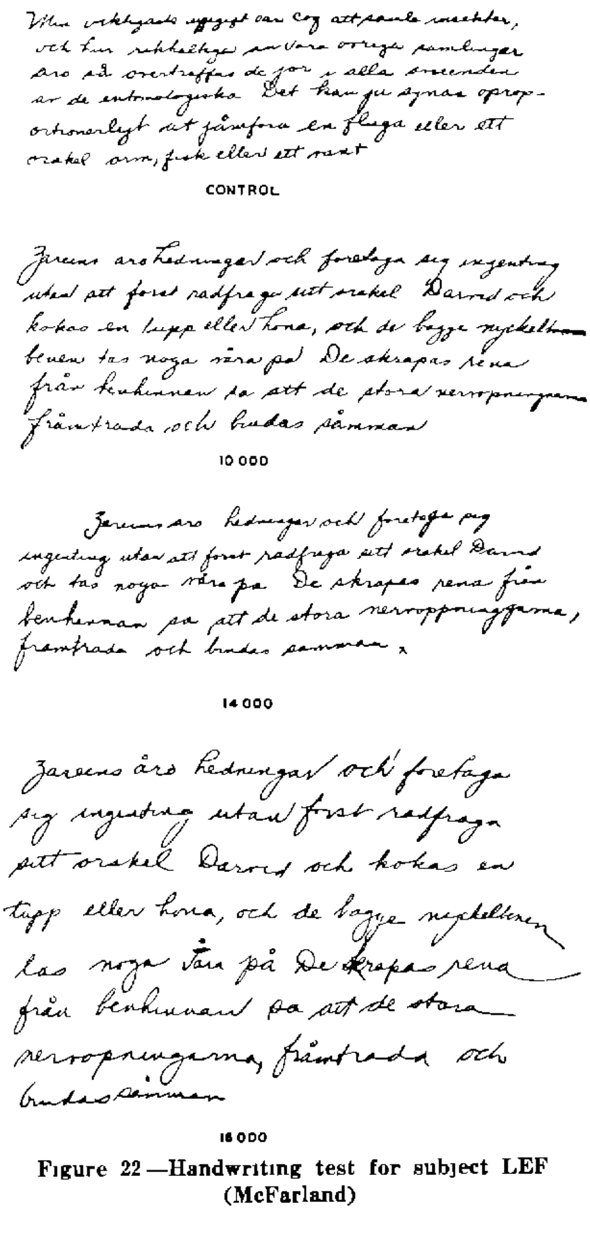


Figure 22 —Handwriting test for subject LEF (McFarland)

dredths of a second with the portable choice reaction time box (61) were not significantly lowered until the partial pressure of oxygen

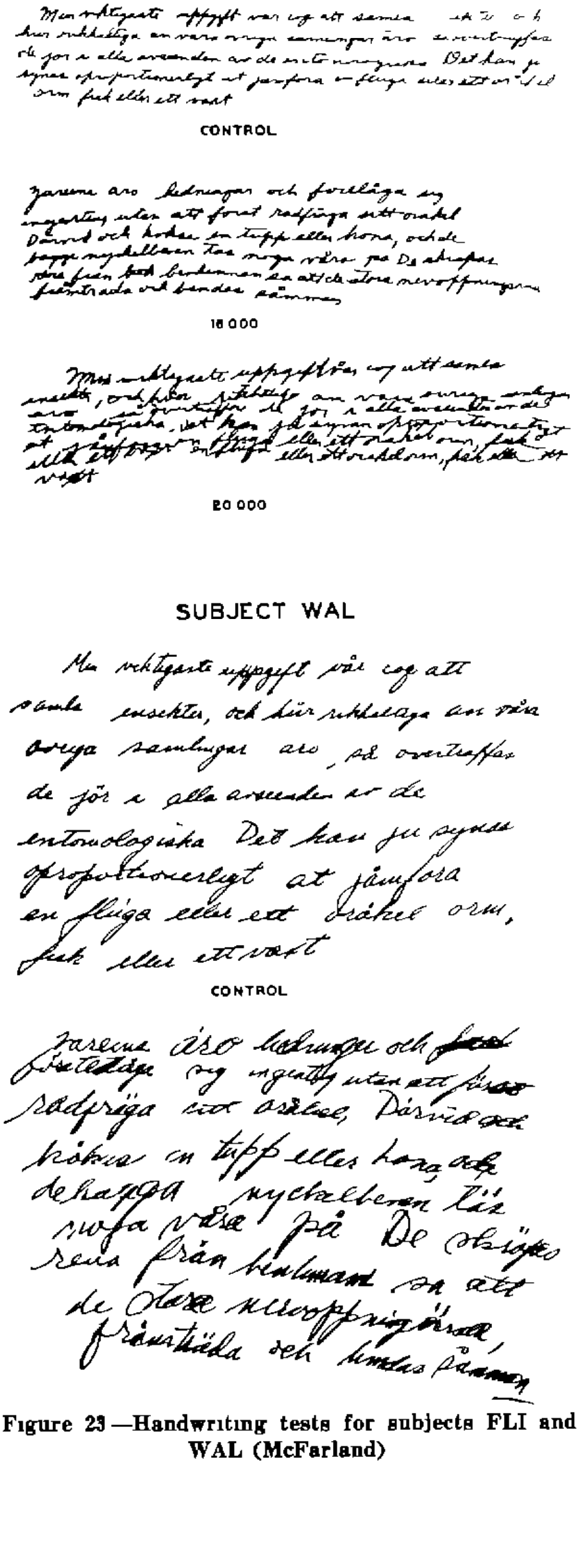
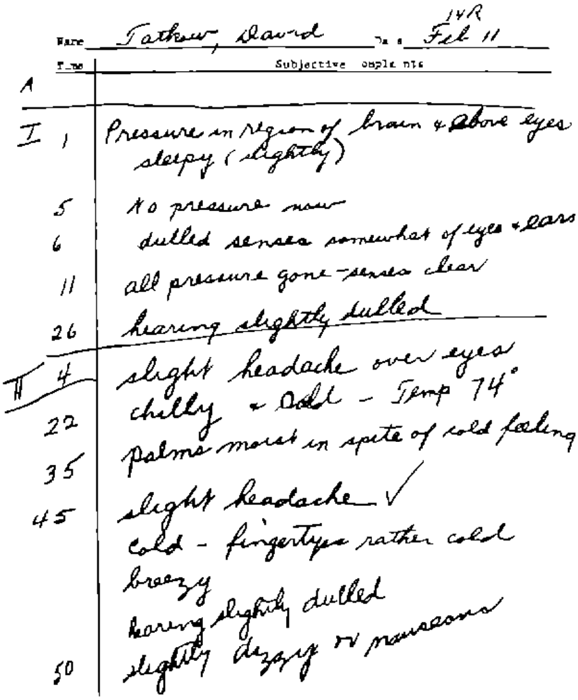


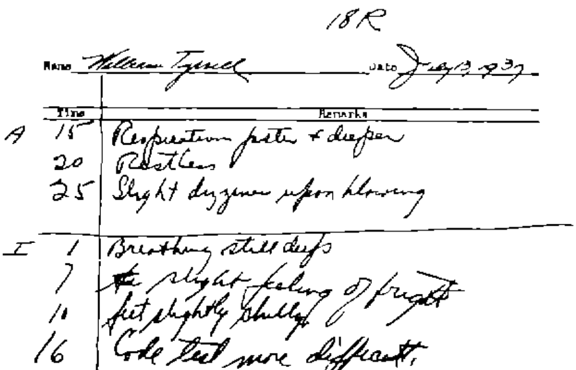
Figure 23 —Handwriting tests for subjects FLI and WAL (McFarland)


14R

Name Tatkow, David Date Feb 11

Time	Subjective complaints
A	
I 1	Pressure in region of brain + above eyes sleepy (slightly)
5	No pressure now
6	dulled senses somewhat of eyes + ears
11	all pressure gone—senses clear
26	hearing slightly dulled
II 4	slight headache over eyes
	chilly + cold – Temp 74°
22	palms moist in spite of cold feeling
35	slight headache ✓
45	cold – fingertips rather cold
	breezy
	hearing slightly dulled
50	slightly dizzy or nauseous

Figure 24 —Handwriting—complaints recorded voluntarily by subject Tatkow (McFarland)


18R

Name William Tyrrell Date [illegible]

Time	Remarks
A 15	Respiration faster + deeper
20	Restless
25	Slight dizziness upon blowing
I 1	Breathing still deep
7	slight feeling of fright
11	feel slightly chilly
16	Code test more difficult,

Figure 25 —Handwriting—complaints recorded voluntarily by subject Tyrrell (McFarland)

was reduced so as to simulate an altitude of 14,000 feet and above This particular test was not complex enough to bring out the more subtle mental changes associated with oxygen deprivation, and hence it was not used throughout the entire series of experiments

d Color naming test —In this test the subjects were required to name as rapidly as possible 100 colored squares ($\frac{1}{2}$ inch squares, red, blue, green, black and yellow) arranged in random order The score is given in seconds and errors Individuals vary greatly in the rapidity and the number of errors with which this test can be taken but few can escape the tendency toward "blocking" or naming the wrong color, especially those subjects who are emotionally unstable Previous experiments have shown that following the ingestion of alcohol or acute "fatigue" this tendency toward "mental lag" or blocking is greatly accentuated A careful record was kept by the experimenter of the number of errors i e, the number of times the subject called the color by the wrong name or was blocked in saying the words Both the time score and the error score should be considered in interpreting these data The results are shown in Table 13 and also in Figure 27 in terms of the percent change from the control data

The results show that on the average, the mean impairment in time due to the oxygen deprivation was statistically significant following the rapid ascents to 12,000 feet and above and at 14,000 feet following the slow ascents The variability of response also in-

TABLE 13.—Color Naming

(Altitude in feet)	Time in seconds: Control	Time in seconds: First hour	Time in seconds: Second hour	Errors[2]: Control	Errors[2]: First hour	Errors[2]: Second hour
10 000 rapid						
Mean	51 44	55 28	54 81	1 22	2 25	2 51
S D	8 83	8 80	8 05	0 97	2 09	2 07
Significance[1]		40–60	70–80		2–5	5–10
Index of change	100 0	101 5	100 7	100 0	102 1	102.2
10 000 slow						
Mean	49 16	40 25		0 50	0 67	
S D	3 43	8 11		0 50	0 70	
Significance		90 100			70 80	
Index of change	100 0	100 2		100 0	100 4	
12 000 rapid						
Mean	51 50	53 31	53 59	0 43	0 77	0 79
S D	6 94	8 63	8 32	0 62	1 55	1 04
Significance		0–1	2–5		40–50	10–20
Index of change	100 0	103 5	104 0	100 0	100 7	100 7
12 000 slow						
Mean	50 25	51 37		1 06	2 50	
S D	9 14	8 28		0 73	1 46	
Significance		50–60			5–10	
Index of change	100 0	102 2		100 0	103 1	
14 000 rapid (17–30 yrs)						
Mean	55 19	59 81	60 04	1 65	3 90	3 76
S D	9 72	14 41	14 43	1 40	2 47	2 74
Significance		0–1	0–1		0–1	0 1
Index of change	100 0	108.4	108 8	100 0	104 0	101 5
14 000 rapid (30–45 yrs)						
Mean	62 6	69 22	73 67	1 60	2 86	3 33
S D	16 30	16 97		0 80	2 17	
Significance		10–20			10–20	
Index of change	100 0	110 6	117 7	100 0	102 6	103 7
14 000 rapid (45 yrs or over)						
Mean	67 00	68 20	71 50	1 27	2 48	2 00
S D	9 71	10 89	14 96	0 97	1 51	0 96
Significance		30 40	30–40		2 5	30–40
Index of change	100 0	101 8	106 7	100 0	102 5	101 7
14 000 slow						
Mean	51 83	51 92		0 66	1 25	
S D	4 90	5 83		0 47	1 11	
Significance		10–20			20–30	
Index of change	100 0	104 0		100 0	101 2	
16 000 rapid						
Mean	54 00	60 01	62 07	1 48	2 89	2 62
S D	9 15	12 44	15 43	1 82	3 25	2 01
Significance		0 1	0 1		1–2	2–5
Index of change	100 0	111 1	110 1	100 0	103 0	102 1
16 000 slow						
Mean	50 22	56 00	58 58	1 22	2 22	2 17
S D	9 21	13 67	13 26	1 75	2 50	2 71
Significance		0–1	0–1		10–20	10–20
Index of change	100 0	111 5	110 6	100 0	102 1	102 0
18 000 rapid						
Mean	59 24	70 09			—	—
S D	8 94	12 29				
Significance		0–1				
Index of change	100 0	118 3				

[1] Chances in 100 that the difference from the control could have arisen by chance Five chances in 100 or less are necessary before the significance of the difference is reasonably certain or before chance can be reasonably ruled out

[2] Total possible number of errors is 100

creased with increasing altitude as indicated in the larger standard deviations The increase in errors in this test was statistically significant at 10,000 feet following the rapid ascent This was not true following the slow ascents until a simulated altitude of 14,000 feet was attained

In order to show the mean variability of response at the various simulated altitudes in the color-naming test, the individual responses (in terms of percent change from the control)

TABLE 14—Code Test

(Altitude in feet)	Time in seconds			Errors[2]		
	Control	First hour	Second hour	Control	First hour	Second hour
10,000 rapid						
Mean	127 16	132 22	130 22	0 28	0 69	0 58
S D	26 85	31 17	29 73	66	93	79
Significance[1]		5–10	30–40		5–10	20–30
Index of change	100 0	104.0	102 4	100 0	100 8	100 6
10 000 slow						
Mean	133 00	129 91		07	1 33	
S D	35 64	31 42		74	1 14	
Significance		40–50			30–40	
Index of change	100 0	97 7		100 0	101 3	
12,000 rapid						
Mean	123 14	131 14	135 14	71	7o	1 00
S D	28 36	29 83	31 61	89	80	1 37
Significance		1–2	0–1		90–100	40–50
Index of change	100 0	106 5	109 7	100 0	100 1	100 6
12 000 slow						
Mean	122 25	128. 31		13	1 06	
S D	33 23	33 91		33	59	
Significance		2–5			0–1	
Index of change	100 0	104. 7		100 0	101 8	
14 000 rapid (15–30 yrs)						
Mean	122. 04	131 72	130 31	27	86	96
S D	21 24	23 60	26 05	53	84	1 06
Significance		0–1	0–1		0–1	0-1
Index of change	100 0	107 9	106 8	100 0	101 2	101 4
14 000 rapid (17–45 yrs)						
Mean	159 70	170 06	167 50	70	1 50	1 67
S D	37 46	44 55		78	1 03	
Significance		70–80			10–20	
Index of change	100 0	106 8	104. 5	100 0	101 0	101 0
14,000 rapid (45 yrs and over)						
Mean	176 92	188 7o	162 42	42	75	83
S D	45 92	52 37	27 31	86	72	63
Significance		10–20	1–2		50–60	10–20
Index of change	100 0	106 6	91 8	100 0	100 7	100 8
14,000 slow						
Mean	119 50	130 42		17	1 00	
S D	39 16	58 78		36	0 65	
Significance		20–30			0–1	
Index of change	100 0	109 1		100 0	101 7	
16 000 rapid						
Mean	121 26	135 14	133 55	37	1 20	1 21
S D	16 85	18 36	21 87	61	1 02	1 60
Significance		0–1	0–1		0–1	0–1
Index of change	100 0	111 5	110 2	100 0	101 7	101 7
16,000 slow						
Mean	111 72	124 78	127 36	20	1 37	1 61
S D	13 31	20 80	25 80	42	1 77	1 40
Significance		0–1	0–1		2–5	0–1
Index of change	100 0	111 7	114 0	100 0	102 3	102 8
18 000 rapid						
Mean	126 03	147 83	156 66	2 61	3 64	2 45
S D	24 33	36 87	53 76	3 11	3 34	2 49
Significance		0–1	0–1		0–1	1–2
Index of change	100 0	117 3	124 3	100 0	102 2	99 7
21,000 rapid						
Mean	128 79	215 33		1 0	21 67	
S D						
Significance		0–1			0–1	
Index of change	100 0	166 8		100 0	173 0	

[1] Chances in 100 that the difference from the control could have arisen by chance Five chances in 100 or less are necessary before the significance of the difference is reasonably certain, or before chance can be reasonably ruled out

[2] Total possible number of errors is 60

for the score (time) and average increase in number of errors have been tabulated on scatter diagrams in Figure 28 These scatter diagrams indicate that there is a fairly wide range in individual differences, but that on the average there is a considerable degree of im-

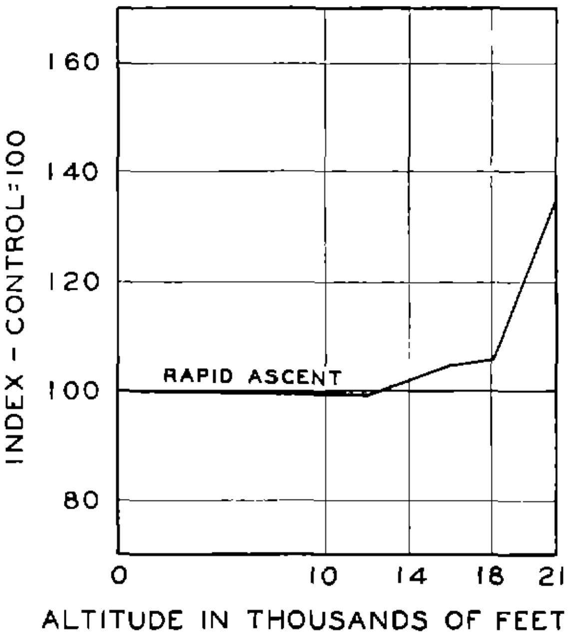


Figure 26 —Choice reaction time test (McFarland)

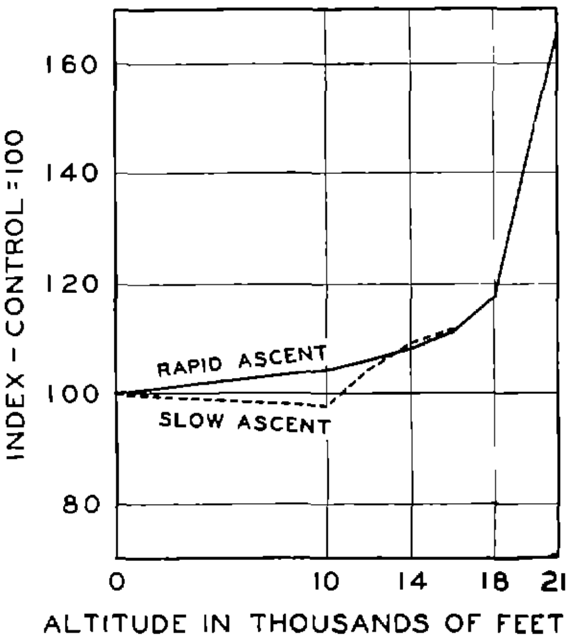


Figure 27 —Color naming test (McFarland)

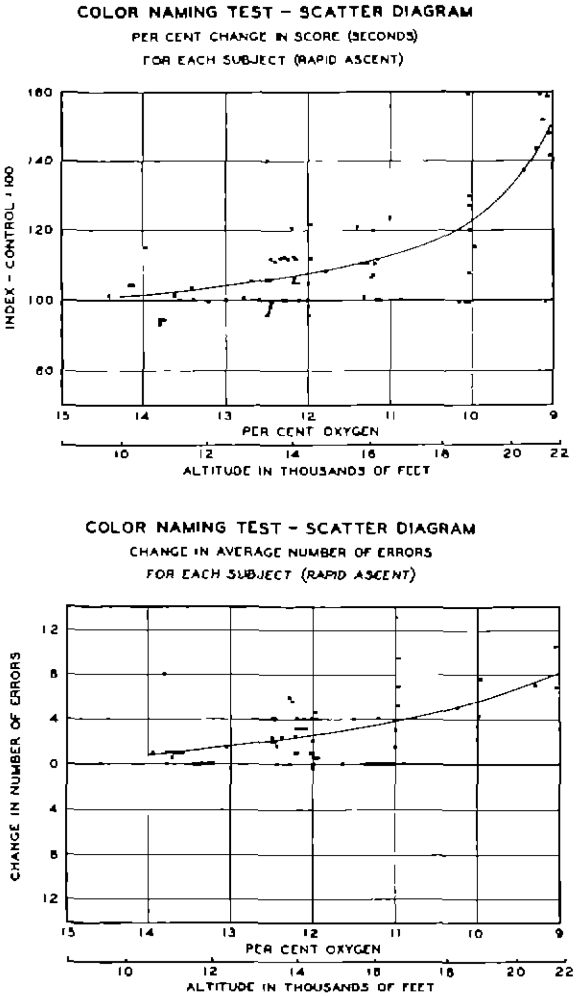


Figure 28 —Scatter diagrams of color naming tests for means and errors (McFarland)

pairment with increasing depletion of the oxygen in the inspired air

e The code test —This test measures the speed and accuracy of transliterating 50 letters of a code There are 40 forms and since each one is different the increased performance due to practice is not significant The test measures a fairly wide range of psychological functions, including close attention, accuracy, adjustments of accommodation and convergence and handwriting

The results of this test, both the mean scores for time and errors, under the various degrees of oxygen deprivation are shown in Table 14 and graphically in Figure 29 Following the rapid ascent to 10,000 feet, there was a significant impairment during the first hour but not during the second hour. These mean decreases in time and errors became statistically reliable at simulated altitudes of 12,000 feet and above. At the highest altitudes the decrease in efficiency in this test became very marked not only as manifested in the mean variability of the group but also in the percent decrease in time and increase in errors. The scatter diagram in Figure 31, showing the individual scores in the code test, illustrates quite clearly the wide range of individual differences, as well as the decrease in scores with an increase in oxygen deprivation.

f. The memory test.—This test (memory for paired associates) measures the capacity for close concentration and immediate memory. Ten pairs of four-letter words (with no obvious associations in terms of meaning) were exposed for 15 seconds each. The cards were then turned over so that only the first of the pair of words was shown. The subject was supposed

TABLE 15.—**Memory and Heterophoria Tests**

(Altitude in feet)	Paired associates			Heterophoria		
	Control	First hour	Second hour	Control	First hour	Second hour
10,000 rapid						
Mean	8.94	7.68	7.41	1.90	1.80	1.80
S. D.	1.12	1.48	1.88	3.27	2.99	2.99
Significance [1]		0–1	0–1		100	100
Index of change [2]	100.0	68.2	62.9		−0.10	−0.10
10,000 slow						
Mean	8.50	8.41		0.60	0.80	
S. D.	0.96	1.63		0.49	0.60	
Significance		10–20			60–70	
Index of change	100.0	98.9			0.20	
12,000 rapid						
Mean	9.33	7.92	9.08	1.58	1.83	2.25
S. D.	0.53	2.38	1.04	2.60	2.49	2.74
Significance		20–30	50–60		40–50	10–20
Index of change	100.0	84.9	97.3		25	67
12,000 slow						
Mean	8.75	7.87		0.87	1.12	
S. D.	0.83	1.48		1.46	1.62	
Significance		20–30			90–100	
Index of change	100.0	89.9			9.25	
14,000 rapid (17–30 yrs.)						
Mean	8.11	5.91	6.50	2.47	2.86	2.88
S. D.	1.99	2.64	3.16	4.19	4.46	3.91
Significance		0–1	0–1		10–20	2–5
Index of change	100.0	72.9	80.8		39	0.41
14,000 rapid (30–45) yrs						
Mean	8.13	6.79	8.5	1.63	2.86	1.33
S. D.	1.24	2.33		2.39	2.76	
Significance		30–40			20–30	
Index of change	100.0	83.5	104.5		1.23	−0.30
14,000 rapid (45 yrs. and over)						
Mean				3.35	2.70	3.75
S. D.				3.90	3.55	2.05
Significance					40–50	
Index of change					−0.65	40
14,000 slow						
Mean	9.00	8.63		0	0.20	
S. D.				68	0.90	
Significance		20–30			60–70	
Index of change	100.0	95.9			0.20	
16,000 rapid						
Mean	7.75	5.91	7.06	2.39	2.69	2.77
S. D.	1.79	2.27	2.18	4.05	3.87	4.12
Significance		1–2	10–20		40–50	30–40
Index of change	100.0	76.3	91.1		31	39
16,000 slow						
Mean	7.33	6.83	7.22	2.56	2.22	3.06
S. D.	1.71	1.67	2.40	3.59	3.21	3.44
Significance		30–40	80–90		40–50	10–20
Index of change	100.0	93.2	98.5		−0.32	50

[1] Chances in 100 that the difference from the control could have arisen by chance. Five chances in 100 or less are necessary before the significance of the difference is reasonably certain, or before chance can be reasonably ruled out.

[2] Index of change for heterophoria is amount of change in prism diopters.

to remember the second or associated word within 5 to 10 seconds

The results of this test are shown in Table 15 and Figure 30 There was a significant decrease in the average number of words recalled

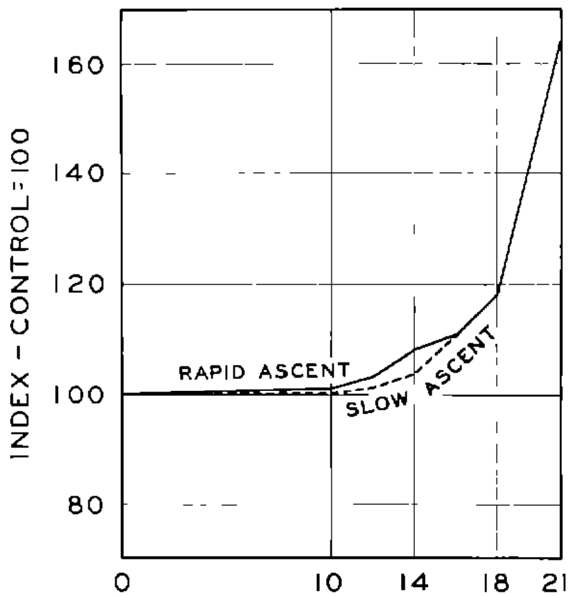


Figure 29—Code test (McFarland)

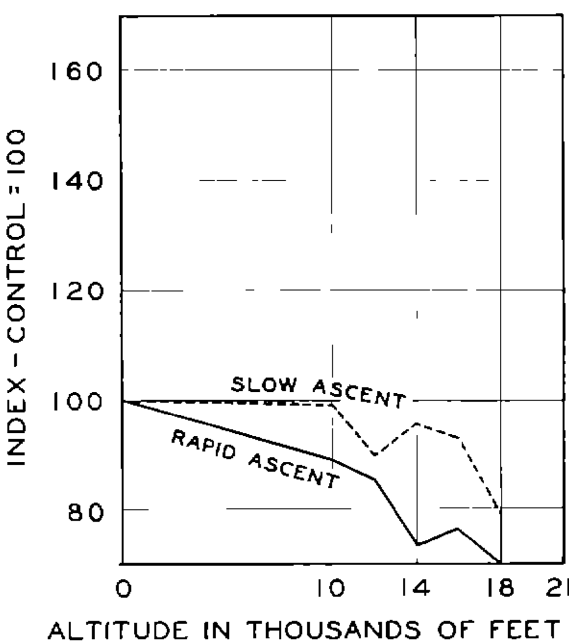


Figure 30—Memory test (McFarland)

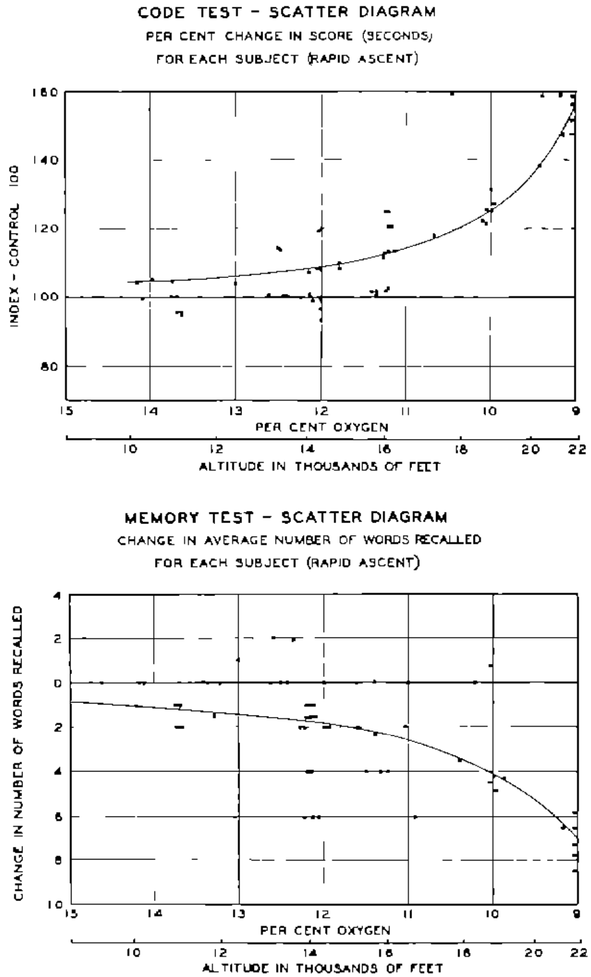


Figure 31—Scatter diagrams for code and memory tests (McFarland)

at 10,000 feet following the rapid ascent The mean decrease was not statistically reliable, however, at 12,000 feet following both the rapid and slow ascents At 14,000 feet and above the impairment in immediate memory was, on the average significant statistically At the higher altitudes (18,000 and 21,000 feeet) (data not shown in Table 15—only in Figure 30) the impairment was very marked

A scatter diagram which indicates the range of individual variability is shown in Figure 31 The scattering in individual scores is greater than in other tests because it is such a difficult one The general tendency for the average subject to be less efficient with increasing oxygen deprivation is very striking

TABLE 16

PHYSIOLOGICAL AND PSYCHOLOGICAL COMPLAINTS

1. Headache Where?________________ YES NO ?
2 Visual or auditory impairment_______ YES NO ?
3 Ringing or buzzing in ears___________ YES NO ?
4. Vertigo or dizziness__________________ YES NO ?
5 Easily fatigued on exertion___________ YES NO ?
6 Nausea or indigestion_________________ YES NO ?
7 Gas on stomach or in intestines______ YES NO ?
8 Cold extremities______________________ YES NO ?
9 Feeling of heat and sweating_________ YES NO ?
10 Muscular stiffness and cramps________ YES NO ?
11 Tremors—fingers, hands, etc__________ YES NO ?
12 Impaired coordination or clumsiness__ YES NO ?
13 Shortness of breath__________________ YES NO ?
14 Periodic or irregular breathing_______ YES NO ?
15 Sighing or long deep breaths_________ YES NO ?
16 Excessive sleepiness__________________ YES NO ?
17 Palpitations or cardiac distress_______ YES NO ?
18. Feel talkative and excited____________ YES NO ?
19 Stuttering or blocking of speech______ YES NO ?
20 Difficulty in concentrating (distractable)_____________________________ YES NO ?
21 Slowness in reasoning________________ YES NO ?
22. Greater effort to carry out tasks______ YES NO ?
23 Mentally lazy_________________________ YES NO ?
24. Feel depressed and grouchy___________ YES NO ?
25 Feel exhilarated and gay_____________ YES NO ?
26 Nervous, high strung, inward tension__ YES NO ?
27 Sudden changes in mood______________ YES NO ?
28 Fidgety or restless___________________ YES NO ?
29 Worry excessively about health_______ YES NO ?
30 Feel indifferent and exhausted________ YES NO ?

5 *Physiological and psychological complaints*—In an attempt to follow the relative amount of impairment in each subject, from the point of view of general discomfort or subjective complaints, two different tests were used First, each subject was asked to write a running account of his physiological and psychological subjective feelings or impairment, and, second, a standardized test of complaints (cf Table 16) was arranged on the basis of the most frequent reactions observed in previous experiments in reduced oxygen pressure both in chambers at sea level and while in flight at high altitude

The most frequent complaints recorded voluntarily by each subject at simulated altitudes of from 10,000 feet to 16,000 feet (rapid ascents) are shown in rank order as to frequency in Table 17 At 10,000 feet, for example, 10 5 percent of the subjects reported headaches, at 12,000 feet, 33 3 percent, at 14,000 feet, 62 4 percent, and at 16,000 feet, 66 7 percent The results in this test are also shown graphically in Figure 32 The curves were charted so as to show the time when the various complaints were first observed (cumulative) and also what percent of each group developed the symptoms during each experimental period For example, during the rapid ascents to 16,000 feet, 10 minutes after the altitude had been simulated, 40 percent of the group experienced headaches By the end of the first hour, however, approximately 70 percent of the subjects had a headache which persisted, on the average, until the end of the experiment

The results obtained from the questionnaire (cf Table 16) are shown in Table 18 and Figure 33 for the various altitudes following both rapid and slow ascents in terms of frequency The various questions have been classified into circulatory, respiratory, digestive, muscular (exertion), sensory, and psychological complaints in order to show the percentage of the subjects who experienced these different complaints at the various altitudes

The results of these two tests correspond closely, which indicates that this procedure in recording the various complaints was quite reliable These data also show that with increasing altitude the average subject is consistently impaired by the lowered partial pressure of oxygen Comparing the rapid and slow ascents in Figure 33, it also appears that, on the average, a smaller percentage of each group is affected by the oxygen deprivation following the slow ascents in comparison with the rapid ones

TABLE 17

MOST FREQUENT COMPLAINTS NOTED VOLUNTARILY BY SUBJECTS AT THE ALTITUDES SHOWN FOLLOWING RAPID ASCENTS

Complaints	10,000 feet	12,000 feet	14 000 feet	16 000 feet
	Percent	*Percent*	*Percent*	*Percent*
Headache	10 5	33.3	62.4	66 7
Respiratory changes or difficulties	26 3	16 7	42.5	60 0
Excessive sleepiness	21 1	50 0	37 5	20 0
Vertigo or dizziness	5 3	0	32.5	53 3
Difficulty in concentrating	21 1	16 7	5 0	46 7
Sensory impairment	5 3	16.7	30 0	33 3
Lassitude, indifference	21 1	16 7	25.0	13 3
Fatigue	5 3	0	27 5	33 3

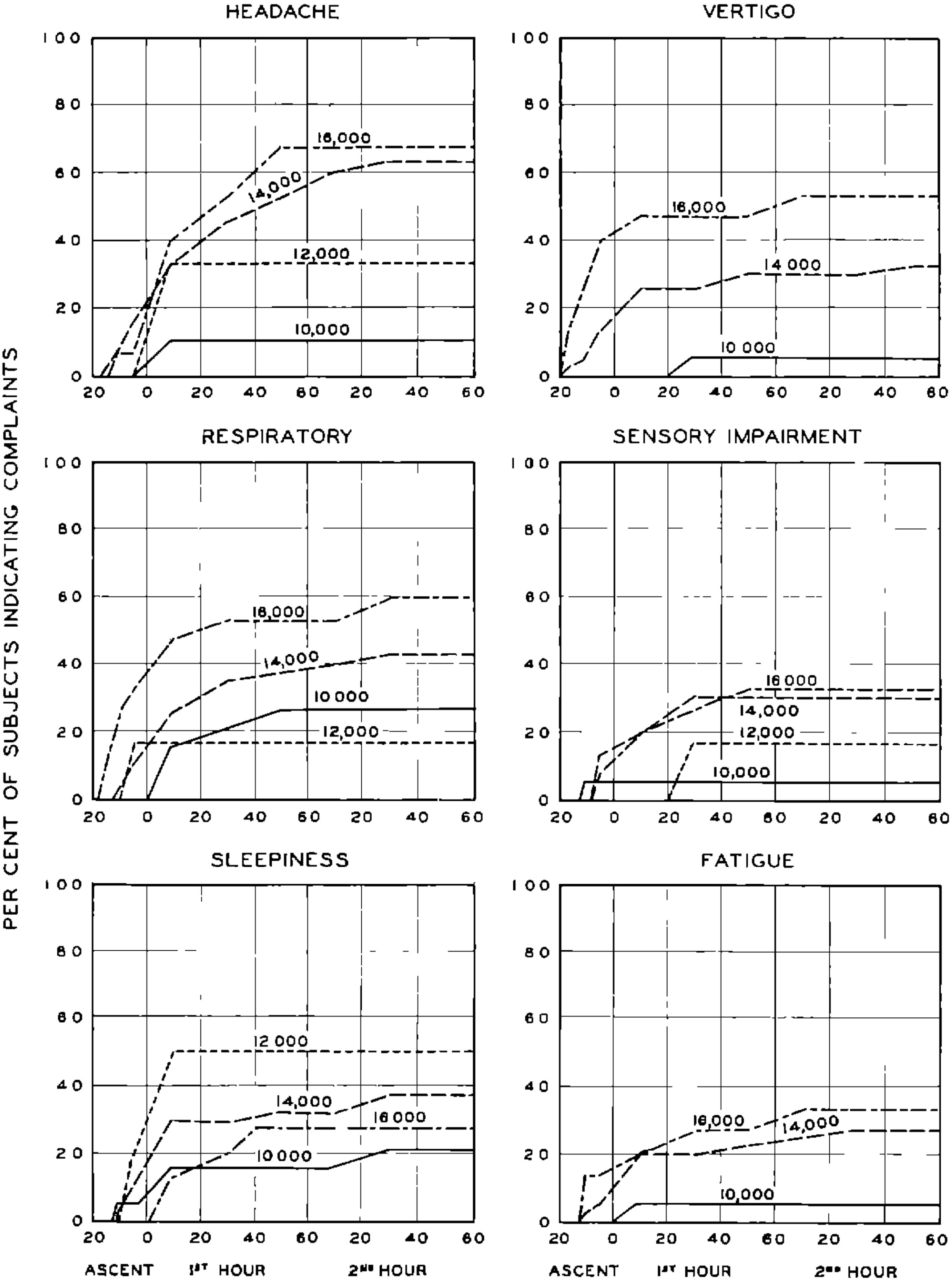


Figure 32 —Complaints reported voluntarily during rapid ascents (cumulative) (McFarland)

TABLE 18 —**Frequency of the various physiological and psychological complaints**

	10,000 ft rapid			10,000 ft slow			12,000 ft rapid			12,000 ft slow			14,000 ft rapid			14,000 ft slow			16,000 ft rapid			16,000 ft slow		
	Yes	No	?	Yes	No	?	Yes	No	?	Yes	No	?	Yes	No	?	Yes	No	?	Yes	No	?	Yes	No	?
Circulatory	0	94.5	5.5	0	100.0	0	14.4	85.6	0	0	87.5	12.5	4.2	87.3	8.5	0	100.0	0	26.3	68.4	5.3	11.8	88.2	0
Palpitations or cardiac distress	0	94.5	5.5	0	100.0	0	14.4	85.6	0	0	87.5	12.5	4.2	87.3	8.5	0	100.0	0	26.3	68.4	5.3	11.8	88.2	0
Respiratory	18.5	75.9	5.6	11.2	83.3	5.5	26.2	71.4	2.4	37.5	58.4	4.1	34.3	59.3	6.4	22.2	77.8	0	43.8	47.4	8.8	25.5	70.6	3.9
Shortness of breath	11.2	83.3	5.5	0	83.3	16.7	28.6	71.4	0	25.0	62.5	12.5	27.7	61.6	10.7	16.6	83.4	0	36.8	52.6	10.6	23.5	70.6	5.9
Periodic or irregular breathing	16.7	77.8	5.5	16.7	83.3	0	14.4	85.6	0	37.5	62.5	0	27.7	65.9	6.4	16.6	83.4	0	42.1	42.1	15.8	17.6	76.5	5.9
Sighing or long deep breaths	27.8	66.7	5.5	16.7	83.3	0	35.7	57.2	7.1	50.0	50.0	0	46.8	51.1	2.1	33.3	66.7	0	52.6	47.4	0	35.3	64.7	0
Digestion	8.2	89.0	2.8	8.4	91.6	0	10.7	82.1	7.2	6.2	81.3	12.5	13.8	83.0	3.2	0	100.0	0	21.0	76.4	2.6	14.7	79.5	5.8
Nausea or indigestion	0	100.0	0	0	100.0	0	0	92.9	7.1	0	87.5	12.5	6.4	89.4	4.2	0	100.0	0	10.5	84.2	5.3	5.9	82.4	11.7
Gas on stomach or in intestines	16.7	77.8	5.5	16.7	83.3	0	21.4	71.5	7.1	12.5	75.0	12.5	21.3	76.6	2.1	0	100.0	0	31.6	68.4	0	23.5	76.5	0
Exertion (Muscle)	11.9	86.5	1.6	9.5	88.1	2.4	16.3	72.4	11.3	12.5	76.8	10.7	25.2	67.4	7.4	7.1	90.5	2.4	36.1	57.1	6.8	27.7	68.1	4.2
Impaired coordination or clumsiness	16.7	83.3	0	16.7	83.3	0	21.4	64.2	14.4	25.0	62.5	12.5	25.5	70.2	4.3	16.6	83.4	0	31.6	52.6	15.8	29.4	70.6	0
Easily fatigued on exertion	11.2	83.3	5.5	16.7	83.3	0	21.4	78.6	0	12.5	75.0	12.5	27.7	57.4	14.9	16.6	83.4	0	36.8	52.6	10.6	23.5	64.8	11.7
Muscular stiffness and cramps	11.2	88.8	0	0	83.3	16.7	0	85.6	14.4	0	100.0	0	6.4	91.5	2.1	0	100.0	0	21.0	73.7	5.3	17.6	76.5	5.9
Tremors—fingers, hands, etc	11.2	88.8	0	16.7	83.3	0	21.4	71.5	7.1	12.5	75.0	12.5	17.0	78.6	4.4	0	100.0	0	47.4	42.1	10.5	29.4	64.7	5.9
Excessive sleepiness	16.7	83.3	0	0	100.0	0	28.6	64.3	7.1	37.5	62.5	0	42.6	44.6	12.8	0	100.0	0	47.4	52.6	0	41.2	52.9	5.9
Stuttering or blocking of speech	0	94.5	5.5	0	100.0	0	7.1	85.8	7.1	0	87.5	12.5	6.4	87.2	6.4	0	100.0	0	15.8	78.9	5.3	5.9	94.1	0
Greater effort to carry out tasks	16.7	83.3	0	16.7	83.3	0	14.3	57.1	28.6	0	75.0	25.0	51.0	42.5	6.5	16.6	66.8	16.6	52.6	47.4	0	47.1	52.9	0
Sensory	6.5	93.5	0	8.4	91.6	0	19.0	77.4	3.6	12.5	85.4	2.1	25.5	70.2	4.3	11.1	88.9	0	36.0	57.9	6.1	29.4	65.7	4.9
Headache	11.2	88.8	0	16.7	83.3	0	42.8	42.8	14.4	25.0	75.0	0	61.7	36.2	2.1	0	100.0	0	78.9	15.8	5.3	52.9	47.1	0
Visual or auditory impairment	11.2	88.8	0	16.7	83.3	0	7.1	92.9	0	12.5	87.5	0	19.1	80.9	0	0	100.0	0	36.8	47.4	15.8	23.5	64.7	11.8
Ringing or buzzing in ears	0	100.0	0	0	100.0	0	0	100.0	0	0	100.0	0	6.4	91.5	2.1	0	100.0	0	10.5	89.5	0	5.9	94.1	0
Cold extremities	5.5	94.5	0	16.7	83.3	0	57.2	42.8	0	12.5	75.0	12.5	27.7	61.6	10.7	50.0	50.0	0	52.6	42.1	5.3	47.0	41.2	11.8
Feeling of heat and sweating	5.5	94.5	0	0	100.0	0	7.1	92.9	0	12.5	87.5	0	17.0	78.8	4.2	0	100.0	0	5.3	97.4	5.3	11.8	82.3	5.9
Vertigo or dizziness	5.5	94.5	0	0	100.0	0	0	92.9	7.1	12.5	87.5	0	21.2	72.4	6.4	16.6	83.4	0	31.6	63.1	5.3	35.3	64.7	0
Psychological	9.6	86.3	4.1	12.1	84.8	3.1	16.9	78.6	4.5	4.5	81.8	13.7	19.5	75.8	4.7	12.1	86.4	1.5	21.1	71.3	7.6	21.4	77.0	1.6
Feel talkative and excited	11.2	83.3	5.5	16.7	83.3	0	7.1	85.8	7.1	0	87.5	12.5	21.2	70.3	8.5	16.6	83.4	0	31.6	63.1	5.3	11.8	88.2	0
Difficulty in concentrating (distractable)	5.6	88.8	5.6	0	100.0	0	35.7	64.3	0	12.5	62.5	25.0	36.2	61.7	2.1	16.6	66.8	16.6	42.1	57.9	0	35.3	64.7	0
Slowness in reasoning	5.6	88.8	5.6	16.7	66.6	16.7	7.1	85.8	7.1	0	87.5	12.5	21.3	63.8	14.9	16.6	83.4	0	21.1	68.4	10.5	29.4	64.7	5.9
Mentally lazy	22.2	61.1	16.7	16.7	83.3	0	35.7	64.3	0	12.5	75.0	12.5	42.5	51.1	6.4	33.2	66.8	0	31.6	52.7	15.8	35.3	64.7	0
Feel depressed and grouchy	0	100.0	0	16.7	83.3	0	14.4	85.6	0	0	87.5	12.5	10.6	83.0	6.4	0	100.0	0	10.5	79.0	10.5	11.8	88.2	0
Feel exhilarated and gay	11.2	88.8	0	0	83.3	16.7	14.4	85.6	0	0	87.5	12.5	27.6	70.3	2.1	16.6	83.4	0	15.8	79.0	5.2	17.6	82.4	0
Nervous high strung, inward tension	5.6	88.8	5.6	16.7	83.3	0	0	92.9	7.1	0	87.5	12.5	12.8	85.1	2.1	0	100.0	0	10.5	79.0	10.5	11.8	88.2	0
Sudden changes in mood	0	100.0	0	0	100.0	0	14.4	78.5	7.1	0	87.5	12.5	6.4	91.5	2.1	0	100.0	0	15.8	79.0	5.2	17.6	76.5	5.9
Fidgety or restless	22.2	72.3	5.5	16.7	83.3	0	28.6	64.3	7.1	12.5	75.0	12.5	25.5	72.4	2.1	33.2	66.8	0	31.6	63.1	5.3	35.3	58.8	5.9
Worry excessively about health	0	100.0	0	16.7	83.3	0	0	92.9	7.1	0	87.5	12.5	0	97.9	2.1	0	100.0	0	0	94.7	5.3	5.9	94.1	0
Feel indifferent and exhausted	22.2	77.8	0	16.7	83.3	0	28.6	64.3	7.1	12.5	75.0	12.5	10.6	87.3	2.1	0	100.0	0	21.1	68.4	10.5	23.5	76.5	0
Total	10.1	87.1	2.8	10.0	87.8	2.2	17.4	76.9	5.7	11.3	79.2	9.5	22.6	72.0	5.4	10.6	88.3	1.1	30.0	63.1	6.9	24.1	72.5	3.4

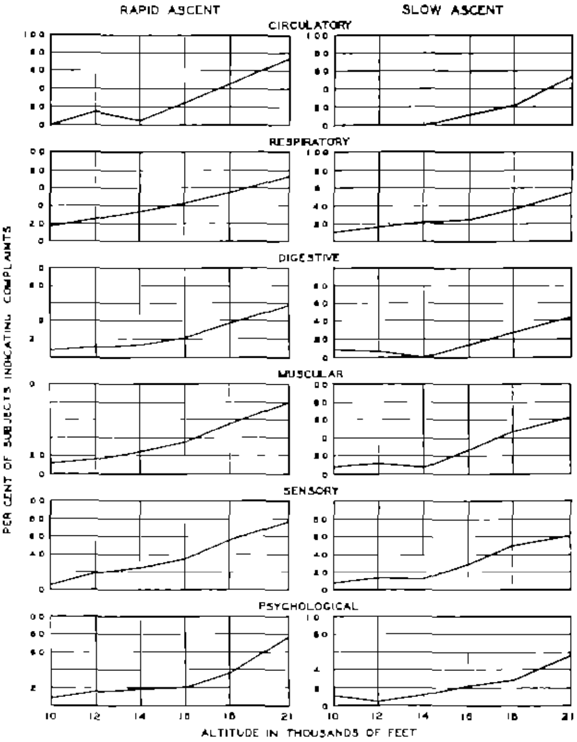


Figure 33—Frequency of the various physiological and psychological complaints (McFarland)

V Results of the Experiment Dealing With Age in Relation to Acclimatization to High Altitude (Part II)

Since a large number of the passengers who fly on the commercial air transport planes are fairly advanced in years, an attempt has been made to find out whether older persons are impaired by oxygen deprivation to a relatively greater extent than younger persons

At the Harvard Fatigue Laboratory during the past two years an extensive investigation has been made of the physiological responses of persons (total number 79) varying in age from 6 to 75 years to several standard grades of work on the treadmill The subjects came to the laboratory in a basal state and were asked to respond to 3 metabolic rates (1) rest, (2) walking (moderate work), and (3) running (maximal work) On the average, the pre- and post-adolescents were more variable in their physiological responses than the older subjects One of the most striking results of the investigation was the gradual decrease in the maximal heart rate with increasing age under conditions of maximal work Through the kindness of S Robinson and D B Dill,[7] the results obtained in the studies of the heart rate are shown in Figures 34 and 35 in the form of scatter diagrams When the highest heart rate attained in maximal work was plotted against age, the range was from 210 beats per minute for the younger subjects to 155 beats per minute at the opposite extreme, i e, for the older subjects (cf Figure 34) The median pulse rates in Figure 35 show the same general tendency It is of special interest to observe in Figure 35 that this tendency was manifested in the younger subjects even while waiting to get on the treadmill before the experiment began On the average, therefore, it appears that the younger subjects tend to manifest more flexi-

[7] Robinson S, Experimental Studies of Physical Fitness in Relation to Age Arbeitsphysiologie Vol 10 pp 251–323 1938

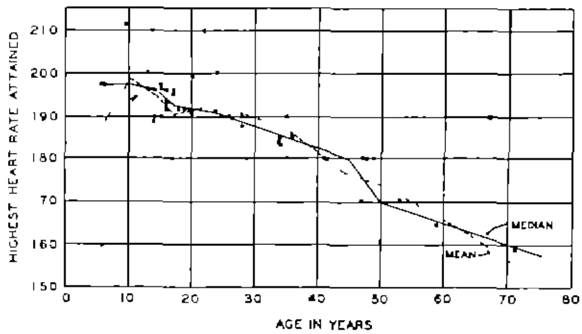


Figure 34—Heart rate in maximal work at various ages (Robinson and Dill)

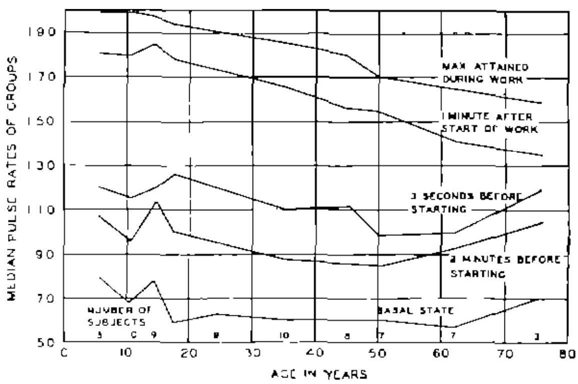


Figure 35—Heart rate before and during work (Robinson and Dill)

ble or less stabilized cardiovascular systems in responding to a fixed stress such as running on the treadmill

It is interesting, and quite relevant probably, to compare the results obtained in the above experiment with the response of older subjects to the stress of oxygen deprivation encountered during flights to high altitudes Three groups of subjects were compared during a rapid ascent to 14,000 feet This altitude was selected since it seemed to be high enough to accentuate differences in physiological and psychological make-up and adaptability

The groups varied in age as follows (1) 50 subjects, 17 to 30 years, (2) 15 subjects, 30 to 45 years, and (3) 16 subjects, 45 to 72 years As indicated previously, the younger men were all college students or graduates from the University, and the others were business and professional men from New York City

The results of the tests for pulse rate, systolic and diastolic blood pressure, and alveolar air are shown in Tables 8 9, 10 & 11, respectively, The average increase in pulse rate for each group is plotted in relation to time in Figure 36 The results indicate that the older subjects show less extreme circulatory responses to oxygen deprivation as manifested in pulse rate per minute than the younger subjects This observation is in agreement with the findings of Robinson and Dill in regard to increases in pulse rate under conditions of maximal work We also observed that the younger subjects were more susceptible to fainting under low oxygen than the older subjects

The group differences in systolic blood pressure were not very striking, as shown in Figure 37 There was a general tendency, however, for the diastolic blood pressure to increase toward the end of each experiment in the 45 to 72 age group In the age group under 30 years, the diastolic pressure showed a higher initial increase than was the case with the two other groups The partial pressure of oxygen in the alveolar air was, on the average, higher in the 45 to 72 age group than in the two younger groups throughout each experimental period (cf Table 11) The difference was 4 4 mm Hg during the second hour Since the respiratory and cardiovascular responses were less extreme in the older subjects, it is not surprising that the partial pressure in the alveolar air was significantly higher

In comparing the results of the three age groups in the psychological tests (cf Tables 13, 14, and 15) the average impairment in the color naming, code, and phoria tests was no greater for the 45 to 72 age group than for the two younger groups The older subjects, on the average, made poorer control scores than the younger ones, however, if one takes the percentage of change of the low oxygen series compared with the control index of 100, then the impairment shown by the different age groups was of the same magnitude

VI Results of the Experiments Dealing With Physical Fitness in Relation to Acclimatization to High Altitudes (Part III)

1 *Rate of ascent and altitude in relation to physical fitness* —In this part of the experiment an attempt was made to contrast the effects of rapid and slow ascents to high altitudes in the same group of individuals An attempt was made to secure subjects varying in physical fitness so that the ones in training could be contrasted with those in poor physical condition Such an experiment seemed relevant to some of the practical problems encountered in commercial aviation since many passengers acclimatize fairly easily to high altitudes during slow ascents but are quite severely influenced by the reduction in oxygen pressure during rapid ascents The partial pressure of oxygen was varied so as to simulate altitudes of 16,000 feet within 30 minutes (rapid ascent) and 1 hour and 15 minutes (slow ascent) The group was also studied during a rapid ascent to 12,000 feet within 15 minutes Previous experiments had indicated that very slow ascents to 12,000 feet would probably cause only minor variations in the tests

The subjects ranged in age from 19 to 25 years They were selected at random from a group of students in Columbia College and the College of Physicians and Surgeons None of them was suffering from any known organic ailment As far as could be judged from the physiological tests of "fitness" like the Schneider

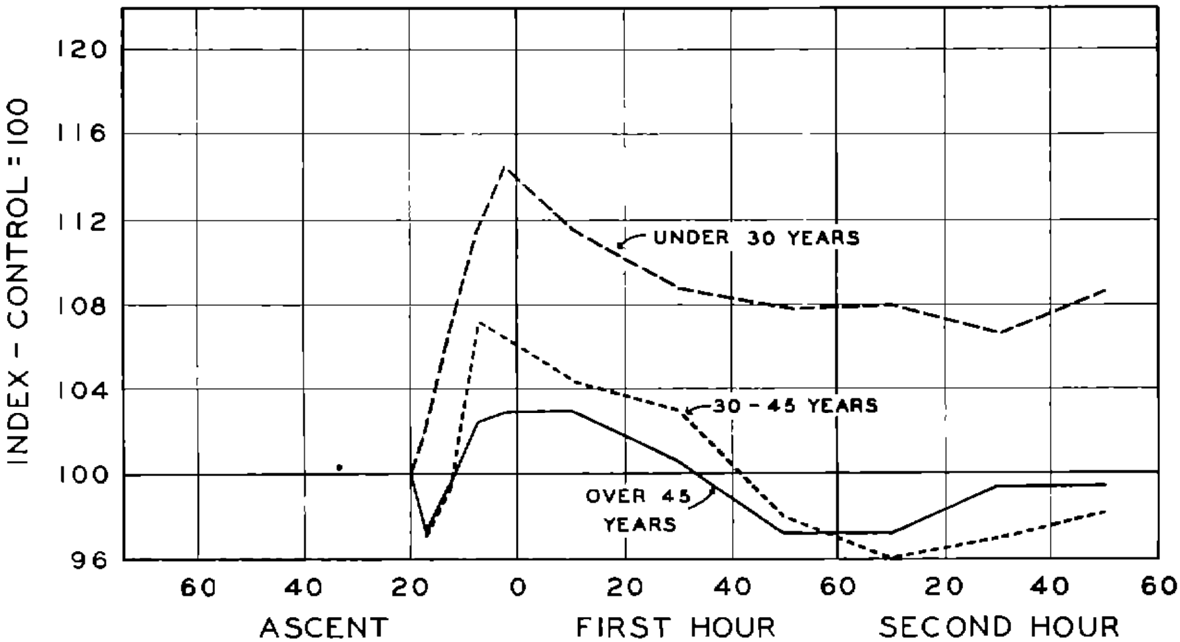


Figure 36 —Pulse rate during rapid ascent and during 2 hours at 14,000 feet for three age groups (McFarland)

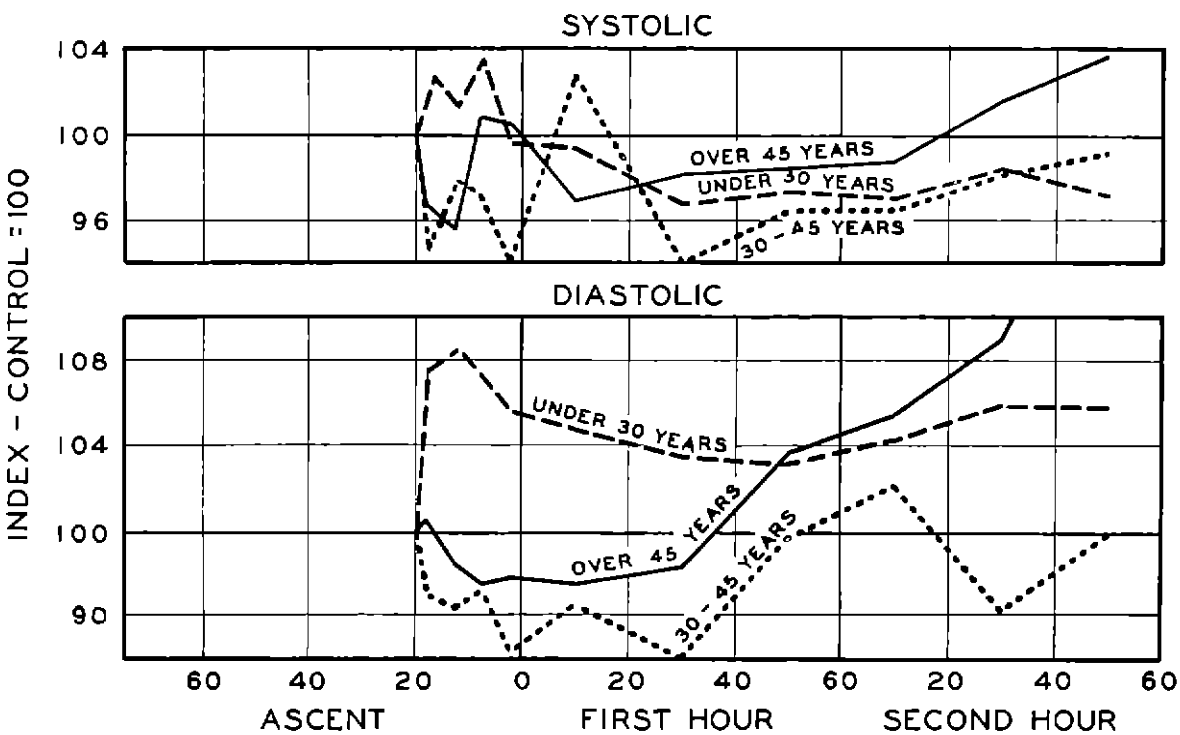


Figure 37 —Blood pressure during rapid ascent and during 2 hours at 14,000 feet for three age groups (McFarland)

Index, basal metabolism, and vital capacity, they were quite representative of the "average run" of young college men, the group containing several subjects in rather poor physical condition and a number in unusually good physical condition (For example, Houston, subject No 10 (cf Table 23), an experienced mountaineer who climbed to an altitude of 25,000 feet last summer on a Himalayan Expedition) Each subject came to the laboratory three times, following the initial practice sessions, at intervals of approximately one week The subjects were very cooperative throughout the series They were not informed as to the purpose of the experiment until the end

The general reactions to the three different rates of ascent may be briefly summarized as follows

Rapid ascent, 16,000 feet—Five of the ten subjects collapsed and one approached collapse In three of the poorest subjects collapse occurred at the end of the first hour and the other two toward the end of the second hour One subject, No 6, developed very marked tonic-clonic cramps from his lower extremities upward and had to be removed from the chamber Upon being removed to the air and breathing a mixture of oxygen and carbon dioxide, these reactions became markedly intensified Collapse in the other cases was accompanied by sudden and extreme changes in either pulse or blood pressure

Slow ascent, 16,000 feet—This rate of ascent seemed to allow more time for acclimatization, and in general the responses of most of the subjects were less severe Only two of the subjects actually collapsed during this series Four of them, however, were impaired sufficiently to do rather poorly in the tests

Rapid ascent, 12,000 feet—None of the subjects collapsed in this series of tests Subject No 6, however, the one who developed the severe cramps during the rapid ascent to 16,000 feet, had to be removed from the chamber because of a similar kind of response The alterations in pulse and in blood pressures were only slight and usually returned to more normal values toward the end of each experiment There were only very slight changes in the psychological tests in this series

In the treatment of the data the subjects have been divided into two groups, i e , the "fit" subjects or those who adapted easily, and the "unfit" group or those who reacted badly In this way it is possible to contrast the extremes in physical fitness

In Table 19 the effects of a rapid and a slow ascent to 16,000 feet in the various physiological functions are contrasted The average differences in pulse and blood pressure are not great largely because the extremes tend to cancel each other and give somewhat similar means In individual cases the differences were very great During the rapid ascent all of the subjects were affected, the "fit" ones considerably less than the others largely because they became acclimatized during the second hour of each session

TABLE 19

COMPARISON OF RELATIVE EFFECTS OF RAPID AND SLOW ASCENTS ON PHYSIOLOGICAL FUNCTIONS—16 000 FEET

	Pulse (per minute)		Systolic blood pressure (mm Hg)		Alveolar pO_2 (mm Hg)		Alveolar pCO_2 (mm Hg)		Phoria [1]	
	Rapid	Slow	Rapid	Slow	Rapid	Slow	Rapid	Slow	Rapid	Slow
Control	77	80	108	113	104.6	104.5	38.4	36.4	2.7	2.7
First hour	87	84	110	108	42.8	47.6	33.1	34.1	1.6	.7
Second hour	84	85	113	109	39.6	41.9	33.9	33.7	1.9	1.5
End	72	78	107	108						

[1] Deviation from control in prism diopters

TABLE 20

COMPARISON OF RELATIVE EFFECTS OF RAPID AND SLOW ASCENTS ON PSYCHOLOGICAL FUNCTIONS—16,000 FEET

	Code test (time in seconds)		Color naming test (time in seconds)		Reaction time (1/100 seconds)		Dotting test (number hits)	
	Rapid	Slow	Rapid	Slow	Rapid	Slow	Rapid	Slow
Control	109.0	109.0	48.5	48.5	40.9	40.9	287.0	287.0
First hour	139.5	122.0	61.0	63.5	45.3	44.1	251.0	278.0
Second hour	145.0	133.0	60.0	57.5	47.3	44.5	262.0	264.0

TABLE 21.—Comparison of the Differential Effect of Three Runs on Physiological Function of a "Fit" Group (A) and An "Unfit" Group (B)

	Pulse (per minute)		Systolic blood pressure (mm. Hg)		Alveolar pO_2 (mm. Hg)		Alveolar pCO_2 (mm. Hg)		Phoria[1]	
	A	B	A	B	A	B	A	B	A	B
16 000 feet rapid										
Control	77	77	110	10[illegible]	106.7	103.2	36.0	36.2		–
First hour	83	90	11[illegible]	105	41.3	44.2	34.6	33.1	1.3	2.0
Second hour	81	67	111	115	30.6	39.6	33.4	34.5	1.3	2.0
End	79	66	106	107						
16 000 feet slow										
Control	80	80	111	11[illegible]	105.7	103.2	36.6	36.2		
First hour	91	87	109	107	45.6	49.8	34.2	34.0	0	1.4
Second hour	78	93	110	107	43.7	40.0	33.9	33.5	1.3	.7
End	77	79	109	106						
12 000 feet rapid										
Control	78	76	115	103	105.7	103.2	36.6	36.2		
First hour	81	79	114	110	55.1	57.9	35.5	35.3	.7	.7
Second hour	76	77	110	112	57.5	56.1	33.4	33.4	1.3	1.0
End	77	77	110	115						

[1] Deviation from control in prism diopters

The relative impairment in the psychological tests in the slow and rapid ascents is shown in Table 20. The Code test, one of the most reliable since it involves very sustained and accurate attention, showed a significant difference as well as the Color Naming test. The differences in the Choice Reaction and Dotting tests were only slight since the subject could frequently conceal the effects of the oxygen lack by exerting greater effort.

TABLE 22

COMPARISON OF THE DIFFERENTIAL EFFECT OF THREE RUNS ON PSYCHOLOGICAL FUNCTIONS OF A "FIT" GROUP (A) AND AN "UNFIT" GROUP (B)

	Code (time in seconds)		Color naming (time in seconds)		Reaction time (1/100 seconds)	
	A	B	A	B	A	B
16 000 feet rapid						
Control	106	111	47	50	39.8	42.1
First hour	131	148	60	62	43.0	47.0
Second hour	128	162	56	64	45.9	48.7
16 000 feet slow						
Control	106	111	47	50	39.8	42.1
First hour	119	125	51	56	42.3	46.9
Second hour	126	140	55	60	42.3	46.6
12 000 feet rapid						
Control	106	111	47	50	39.8	42.1
First hour	117	130	54	56	42.6	45.1
Second hour	128	139	53	51	42.0	47.4

In Tables 21 and 22 the effects of the various rates of ascent on the physiological and psychological tests for the "fit" and "unfit" subjects are contrasted. The differences in the pulse and blood pressure were less extreme in the group that adjusted most easily; the same tendency was noticeable in the phoria test of ocular muscle balance.

The differences in the psychological tests between the various rates of ascent and height attained are quite significant. In the Code test, for example, the mean score was 128 for the 'fit' group and 162 for those who adapted less easily.

At the end of each experimental session the subjects rated their physiological and psychological changes in accord with the questions in Table 16. The frequency with which each subject was affected in various ways by the oxygen deprivation is indicated in Table 23. It is obvious that the rapid ascent to 16 000 feet caused a greater amount of discomfort than the slow ascent. The total number of complaints in the rapid ascent to 16,000 feet was *105*, in the slow ascent to 16 000 feet, *59* and in the rapid ascent to 12,000 feet, *38*. Figure 38 shows the handwriting of subject J at the time he collapsed following the rapid ascent to 16 000 feet. Figure 39 shows the running account of the same subject's subjective symptoms during the experiment at 12,000 feet (rapid run).

A careful record was kept by each subject of the after-effects of the oxygen deprivation. In the subjects who collapsed the headaches, nausea, palpitations, pain in the chest, and muscular twitchings lasted from one to ten hours. Even in several of the subjects who reacted easily, some of the after-effects mentioned above were noticeable for one to two hours later

In Figures 40 and 41 the results of experiments carried out by McFarland (44) on trans-Andean aeroplanes and trains are contrasted relative to rate of ascent Figure 40 shows that

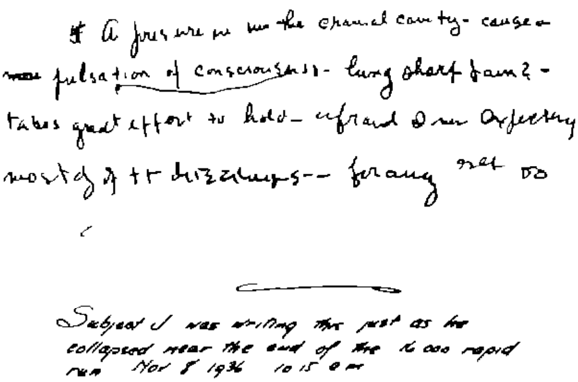


Figure 38 —Handwriting for subject J just previous to collapse (McFarland)

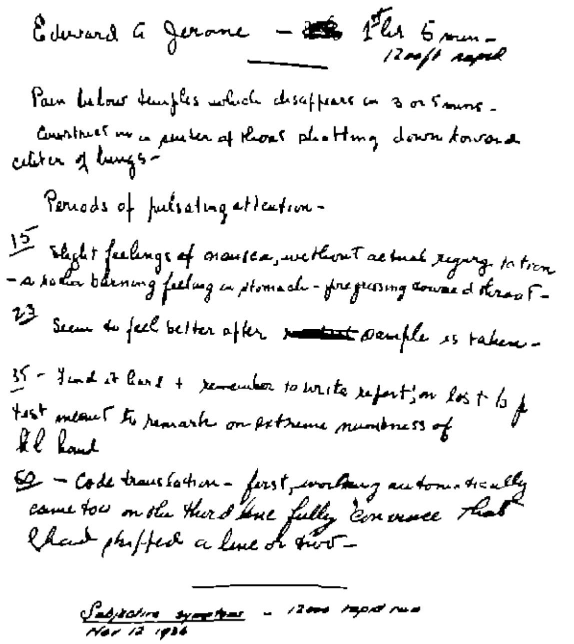


Figure 39 —Subjective symptoms written voluntarily by subject Jerome (McFarland)

TABLE 23 —**Physiological and Psychological Complaints**

[Complaints as checked by the ten subjects after each of the three runs An x represents a complaint, ?, not sure a blank means no complaint]

Complaint [2]	16 000 feet rapid											16 000 feet slow											12 000 feet rapid										
	1	2	3	4	5	6	7	8	9	10	Total	1	2	3	4	5	6 [1]	7	8	9	10	Total	1	2	3	4	5 [1]	6	7	8	9	10 [1]	Total
1		?	x	x	x	x	x	x	x		7	?		x	x	x		x		x		5		?	x	?		x	x				3
2					x	x	x	x			4							?	x	?		1							x				1
3										x	1											0											0
4		x	x	x	x	x	x			x	7		x		x			x				3							?				0
5	?	x		x	x		x		x		5	?						x		?		1				x			x				2
6				x							1											0							?				0
7			x	x			x		x		4			x	x	x		x				4						x	x				2
8	?	x	x	x	x	x	x	x	x	x	9	?	x		x			x	x	x	x	6	x		x	x		x	x	x			6
9											0											0											0
10						x					1											0											0
11	x		x		?	x	x	x	x	x	7	?				x		x			?	2						x	?		x		2
12	?	x		x	x		x		x	x	6		x					x		x		3							x				1
13			x			x			x	x	4							x		x		2		x		x			x				3
14						x	?				1							x				1							x				1
15		x	x			x	x	x			5		x	x				x				4		x		x			?				2
16		x		x	x		x		x		5			x		x		x		x	?	4		x					?		x		2
17						x	?			x	2							x				1							x				1
18		x				x			x	x	4		x									1	?	x									1
19							?	x			1											0							?				0
20		x	x		x		x		x		5							x		x		2							x		x		2
21		x	x		?		?		x		3							x		x	x	3							x		?		1
22		x	x	x	x		x	x	x	x	8		x			x				x	x	4		?					?		?		0
23		x			?		x	?	x	x	4									x	x	2		x					x		x		3
24	?								x		1									x		1									x		1
25		x				x					2		x		x							2		x									1
26						x	?				1											0											0
27			x				x		x		3		x		x							2				x							1
28		x	x						?		2	?	x	x					x		x	4			x				?				1
29											0								x			1											0
30				x	?		x				2								x			1				?			x				1
Total	1	13	12	10	9	13	15	7	15	10	105	0	9	5	6	5		14	5	10	5	59	1	6	3	5		4	13	1	5		38

[1] Not run
[2] The various items listed in this column correspond to the complaints as shown in table 16

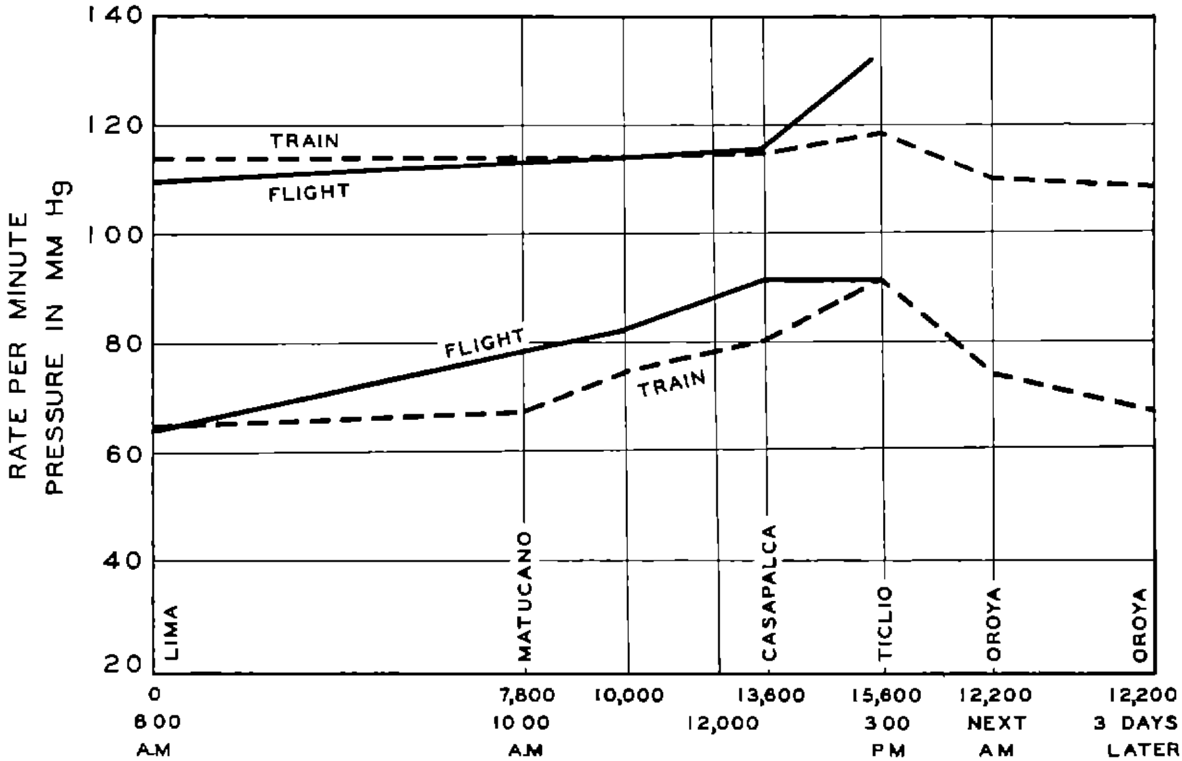


Figure 40 —Pulse rate and blood pressure taken on train between Lima and Oroya (McFarland)

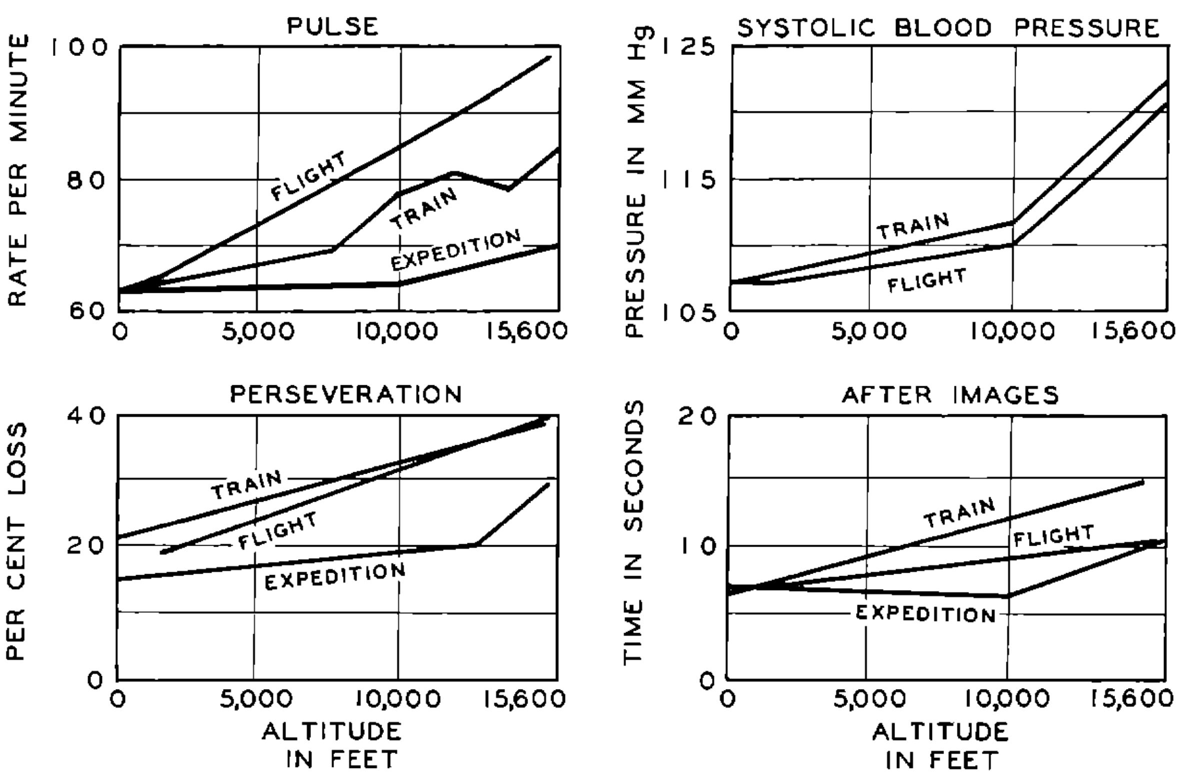


Figure 41 —Comparison of the effects of rapid and slow ascent, subject R M. (McFarland)

the relative increase in pulse rate and systolic blood pressure was greater in the plane when an altitude of approximately 16,000 feet was reached in 20 minutes compared with the more gradual ascent by train to similar altitudes The same tendency is observed in Figure 41, where three rates of ascent to similar altitudes are contrasted, i e, by plane in 20 minutes, by train in 6 to 8 hours, and during gradual acclimatization over two months (cf McFarland (44), International High Altitude Expedition, 1935)

2 *The response of the psychoneurotic group to low oxygen.*—This experiment deals with the responses of 30 normal subjects and 35 psychoneurotic patients to variations in oxygen tension in a low oxygen chamber at sea level Each subject was tested under control conditions or in normal air (21 percent O_2) and in 10 3 percent oxygen, corresponding roughly to 18,000 feet In addition, each subject was given a series of physical fitness tests as a basis for classification The results of these tests are shown in Table 24 (47)

a. The subjects—The control or normal subjects ranged in age from 19 to 30 years and the neurotics from 18 to 35 years The controls were undergraduate and graduate students in Columbia University or instructors and technicians For the most part, they were in good or average health, with normal habits of sleeping, eating, and exercise, and without known organic defects.

The patients were psychoneurotics selected from the Vanderbilt Clinic on the basis of chronic "fatigue and exhaustion", this syndrome being characteristic of all of the patients They were diagnosed (within the more general psychoneurotic classification) for the most part as (1) neurasthenia, (2) anxiety state, or (3) anxiety hysteria They were all ambulatory, cooperative, and of a fairly high level of intelligence, most of them being students or of the so-called "white collar" class They were, on the average, in poor physical condition, but manifested no organic ailments following repeated examinations by the clinicians

b The experimental procedure—The subjects came to the laboratory under basal conditions Following a half-hour rest, a sample of blood was taken Then the subject entered the chamber and was suddenly exposed to the variations in the partial pressure of oxygen The Schneider Index of neurocirculatory fitness was given first, followed by a series of six psychological tests At the end of the experiment a second sample of blood was taken in the chamber and the subject was sent home In case the subject's response was severe, i e, either collapsing or approaching collapse, a small amount of oxygen was administered to facilitate the adaptation The average experimental run lasted two hours

None of the subjects was informed as to the nature of the experiment. The control subjects were simply asked to volunteer for an experiment being given in an air-conditioned room The patients were asked to take a series of diagnostic treatments in attempting to determine more precisely the nature of their illness

In an attempt to judge the reaction of each individual to the diminution in the partial pressure of oxygen, each subject was rated as

TABLE 24 —**Tests of Psychological and Physiological Fitness**

	Normal subjects			Psychoneurotic patients		
	Mean	S D	Range	Mean	S D	Range
Age	24		20 to 34	27		19 to 35
Otis Mental Ability Test (I Q)	125	6 2	117 to 133	106	9 8	80 to 131
Bernreuter Personality Inventory (BI–N)	41			[1] 88		
Basal Metabolic Rate (—)	−8 (12) [2]		−1 to −19	−12 (21)		−3 to −22
Basal Metabolic Rate (+)	+4 (18)		+2 to +14	+9 (14)		+1 to +21
Vital Capacity (cc)	4800		3800 to 6200	4100		2800 to 4700
Holding Breath (in seconds)	74	7 2	50 to 192	45	11 1	38 to 102
Schneider Index	+12 1	1 9	+9 to +17	+7 0	3 9	−3 to +13

[1] High score indicates greater degree of emotional instability
[2] Figures in parentheses indicate number of subjects

to the degree of impairment based on the following criteria

1 *Adapted easily*, a high degree of adaptation, characterized by well-controlled increases in pulse and blood pressure gradually returning to fairly normal reactions and quite normal reactions in the psychological tests
2 *Serious impairment*, but able to continue the tests Marked variations in pulse and blood pressure, and poor response to psychological tests Physical complaints of headache and dizziness, cold extremities flushing of face, pupilary dilation, etc Slight impairment in psychological tests with increased variability
3 *Impending collapse*, followed by removal or oxygen inhalation Extreme variations in pulse and blood pressure, vertigo, severe headache and drowsiness, and sensory and motor impairment
4 *Collapse*, necessitating oxygen inhalation or removal from chamber The cardiovascular reactions were characterized by either a sudden fall in pulse or blood pressure, the one usually closely accompanying the other In these patients the failure of the respiratory center to respond to the oxygen lack appeared to be a very important factor

In Table 25 the percentage of each group reacting according to the above criteria is tabulated

TABLE 25

DEGREE OF ADAPTATION

	Normal Subjects	Psychoneurotics
	Percentage	Percentage
Adjusted easily	40	15
Serious impairment	28	20
Impending collapse	18	21
Collapse	14	44

Table 25 shows that the psychoneurotics were more acutely impaired by the oxygen deprivation than the control subjects Over 44 percent of the patients collapsed within the first 20 minutes and only 14 percent of the normal subjects The effects were sufficiently accentuated, however, in both groups to indicate the danger of sudden exposure to a partial pressure of oxygen corresponding to 18,000 feet

The most common alterations in behavior observed or complained of were sleepiness, yawning tremors of the facial muscles or fingers, vertigo, headache, periods of sweating or coldness (especially in extremities) apathy and indifference, loss of capacity for close attention, impairment of sensory functions unrestricted talking or laughing and loss of memory judgment, and self-criticism

c The cardiovascular reactions—pulse and blood pressure —The Schneider Index of cardiovascular fitness was given to each subject as soon as the partial pressure of oxygen in the chamber was adjusted (within 10 to 15 minutes) In Tables 26 and 27 the mean score on the Schneider Index and the standard deviation for each part of the Index is summarized for the normal and psychoneurotic groups respectively

Upon examination of the tables, one finds that the mean Schneider Index for the normal group was 12 7 in air, and 8 7 in 10 3 percent oxygen The mean Index for the psychoneurotic group was 7 0 in air, +4 8 for approximately 40 percent of the subjects in 10 percent oxygen, and −4 2 for the other 60 percent According to Schneider's observations on aviators 7 0 or below indicated "unfitness," and the pilots were "grounded" or given a vacation The effect of the oxygen deprivation was more severe on the "nervous" subjects as compared to the normal ones These results indicate that the psychoneurotics manifested a definite unfitness in their cardiovascular reactions compared with unselected normal subjects

In analyzing the individual parts of the Index the resting pulse in the control group averaged 62 in air and 76 in 10 percent oxygen, while the resting pulse in the patients was 70 in air and 82 in 10 3 percent oxygen The change in the pulse on standing and after exercise was more extreme in the case of patients compared with the controls In the patients we observed a considerable number of pulse rates which decreased on standing and after exercise This seems to indicate inefficiency and a definite failure of the circulatory system to respond to the extra physical effort. This was especially noticeable just previous to collapse in the 10.3 percent oxygen series. Extreme vertigo and dizziness on standing or after exercise was also accompanied by a sudden fall in pulse rate.

The systolic blood pressure in the patients was slightly higher than in the normal subjects. The extremely high and low blood pressures in the patients tended to cancel out each other and give a more normal mean than was actually the case. This variability is reflected in the greater standard deviations in the scores for the patients.

The most striking difference between the two groups in systolic blood pressure was the tendency on the part of so many of the patients to

TABLE 26.—**Cardio-Vascular Reactions of the Psychoneurotic Group Measured in Terms of the Schneider Index**

	Control		18,000 feet	
	Mean	S. D.	Mean	S. D.
Schneider index	6.9	3.8	4.8 / −4.2	2.3 / 1.7
Pulse reclining	69.8	11.5	81.6	17.4
Pulse standing	87.2	11.5	93.5	16.5
Pulse increase on standing	19.2	8.4 (92% [1])	13.8	23.3 (63% [1])
Pulse decrease on standing	4.4	(10% [1])	9.1	14.7 (29% [1])
Pulse no change on standing				(8% [1])
Pulse after exercise	103.6	14.4	102.6	22.8
Pulse increase after exercise	17.9	9.1 (92% [1])	19.5	14.1 (11% [1])
Pulse decrease	3.8	(8% [1])	18.0	12.8 (77% [1])
Pulse no change		–		(2% [1])
Pulse time to return to normal (secs.)	58.8		66.0	
Systolic B. P. reclining	113.7	12.7	107.4	14.7
Systolic B. P. standing	110.7	14.1	98.7	14.9
B. P. increase	5.0	3.6 (25% [1])	9.8	4.7 (28% [1])
B. P. decrease	6.0	3.7 (65% [1])	15.5	16.7 (62% [1])
B. P. no change		(10% [1])	–	(10% [1])
Diastolic reclining	77.7	16.8	64.0	15.2
Diastolic standing	83.7	11.2	70.1	14.0
Pulse pressure reclining	34.4	8.9	41.8	11.3
Pulse pressure standing	26.6	8.3	28.3	8.6
Pulse pressure increase	5.2	2.4 (13% [1])	7.7	3.9 (11% [1])
Pulse pressure decrease	10.0	6.4 (83% [1])	13.4	16.0 (87% [1])
Pulse pressure no change	--	(4% [1])		(2% [1])

[1] Percent of the group showing an increase, decrease, or no change.

TABLE 27.—**Cardio-Vascular Reactions of the Control Group Measured in Terms of the Schneider Index**

	Control		18,000 feet	
	Mean	S. D.	Mean	S. D.
Schneider index	12.7	1.7	8.7	2.4
Pulse reclining	61.9	6.9	76.5	6.4
Pulse standing	75.6	8.5	88.2	9.5
Pulse increase on standing	13.3	4.7	11.2	7.2
Pulse after exercise	91.5	9.1	104.0	12.6
Pulse increase after exercise	15.3	4.7	18.3	7.9 (95% [1])
Pulse decrease after exercise			12.0	(5% [1])
Pulse time to return to normal (secs.)	116.8	–	178.9	
Systolic B. P. reclining	110.5	9.6	113.7	10.2
Systolic B. P. standing	111.8	8.4	107.0	10.7
B. P. increase on standing	4.1	2.0 (79% [1])	3.7	2.7 (19% [1])
B. P. decrease on standing	3.9	2.4 (11% [1])	10.1	6.1 (68% [1])
B. P. no change on standing				(13% [1])
Diastolic B. P. reclining	76.6	8.4	69.7	10.3
Diastolic B. P. standing	81.0	9.2	69.4	12.2
Pulse pressure reclining	33.6	7.0	43.3	13.4
Pulse pressure standing	30.9	7.4	38.3	15.1
Pulse pressure increase	4.2	2.5 (21% [1])	12.3	6.9 (21% [1])
Pulse pressure decrease	5.2	1.9 (52% [1])	10.4	8.2 (71% [1])
Pulse pressure no change		(27% [1])		(8% [1])

[1] Percent of the group showing an increase, decrease, or no change in blood pressure.

show a decrease on standing rather than an increase. This occurred in over 50 percent of the patients in air (20 percent of the normal subjects) and 62 percent of the patients in 10.3 percent oxygen (45 percent of the normal subjects).

In analyzing the records of 1,050 altitude classification examinations from the rebreather tests given during the World War, Schneider and Truesdell (55) reported two kinds of subjects, the *fainting* and the *nonfainting* types. In the fainting type (46.7 percent falling into this classification), there was frequently a sudden fall in the pulse or blood pressure just previous to collapse, while in the other group (53.3 percent) there was a well-controlled reaction until the very end of the rebreathing test. The altitudes at which members of the two groups became wholly inefficient are indicated in the following table (from Schneider and Truesdell) (65).

TABLE 28

Lowest oxygen tolerated, in percent	Corresponding altitude in feet (000 omitted)	Percent of nonfainting group that became inefficient	Percent of fainting group that became inefficient
11–12	16 –17		0.7
10–11	17 –19.5	0.6	7
9–10	19.5–22	1.2	13.0
8– 9	22 –25	13.0	30.9
7– 8	25 –28	40.1	41.7
Below 7	Above 28	45.2	13.0

In the experiment reported here, many of the psychoneurotic patients apparently belong to the fainting type in that we frequently observed either an uncontrolled rise or fall in pulse or blood pressure upon standing or after exercise.

The Schneider Index appears to be of value in detecting unfitness, but it should be used with additional measures in the case of borderline subjects or those who fall in the middle range of a series. The test should be revised so that the following objections will be taken into account: (1) it gives an undue advantage to subjects with a slow pulse rate, (2) it does penalize the subject who shows a significant fall in pulse rate on standing or after exercise, (3) it fails to take into account body height and weight, the work involved in standing on a chair being much more difficult for a short person than for a tall one, and (4) it is not standardized in relation to age.

TABLE 29

BIOCHEMICAL DETERMINATIONS OF THE CONTROL AND PSYCHONEUROTIC GROUPS

	Control		18,000 feet	
	Before	End	Before	End
Lactic acid in blood				
Control				
Mean	16.32	16.56	10.84	20.96
Standard deviation	2.34	2.55	2.94	4.04
Neurotics				
Mean	17.20	17.91	18.41	24.15
Standard deviation	2.46	2.03	2.57	4.56
Sugar in blood				
Control				
Mean	96.15	96.58	96.35	100.59
Standard deviation	5.68	6.94	5.32	6.50
Neurotics				
Mean	92.49	90.95	91.59	95.57
Standard deviation	7.24	6.00	7.23	8.72
Inorganic phosphorus in serum				
Control				
Mean	4.28	4.36	4.16	4.12
Standard deviation	.63	.61	.60	.50
Neurotics				
Mean	4.24	4.26	4.46	4.17
Standard deviation	.74	.77	.84	.91
Creatinine in blood				
Control				
Mean	1.63	1.67	1.62	1.71
Standard deviation	.20	.21	.20	.24
Neurotics				
Mean	1.47	1.47	1.51	1.63
Standard deviation	.14	.15	.18	.21
Calcium in serum				
Control				
Mean	10.40	10.35	10.81	11.05
Standard deviation	1.14	1.30	1.00	1.38
Neurotics				
Mean	9.94	10.40	10.46	9.46
Standard deviation	1.97	1.73	1.72	2.60

d. The biochemical determinations.—At the beginning of each experimental session a sample of venous blood was taken after a half-hour rest period (fasting state) in air, and again at the end of each period (approximately two hours). In this way it was possible to compare not only the variability of each individual following repeated blood sampling, but also the variability of the groups, as well as any changes due to the anoxemia in the 10 percent oxygen series.

The results of the biochemical tests are summarized in Table 29. On the whole, the differences in the means between the two groups in air compared to 10.3 percent oxygen do not show striking differences. In a number of the patients there were more extreme changes in the lactic acid in low oxygen and wider fluctuations in blood sugar than in the control subjects Possibly this may have been associated with an impairment of the sympathetic nervous system in the patients or more extreme discharges of adrenalin and the consequent mobilization of sugar The lactic acid determinations in the control group were, on the average, lower, and the variability less, than in the patients Many of the patients tended toward the lower range of normal variation in sugar (normal 80 to 120 mg percent) The relative increase in sugar was greater for the patients in the low oxygen series This was also noticeable in the calcium determinations, especially in the low oxygen series The determinations for hemoglobin (results not shown in Table 29) were made only in the low oxygen series There was an average increase of between 4 and 8 percent in both groups, indicating that the percentage of increase in hemoglobin is only of minor importance in facilitating adaptation in flights of short duration

The most striking difference between the two groups was in the greater individual and group variability of the patients, reflecting an organic instability as well as greater difficulty in meeting "emergency" situations or reactions involving stress and flexibility of adjustment In the "nervous" patients the reactions to high altitude are probably accentuated because the sympathetic nervous system, which is usually impaired, is the one most actively involved in bringing about changes in circulation and respiration to adjust to the diminished oxygen

e Psychological tests —In an attempt to get a more objective record of each subject's adjustment to the variations in oxygen tensions psychological tests were given involving quickness and accuracy of motor coordination judgment, perseveration, and attention, or capacity to carry out standardized mental tasks In addition to the objective tests, a record was kept by the experimenter of any obvious changes in mood or emotional reactions as well as alterations in motor coordination tremors indifference or lethargy, etc

The results of the psychological tests are shown in Table 30 On the average, the patients were more severely affected by the oxygen deprivation than the normal subjects The mean scores are not only lower, but there is also a considerable increase in the variability (standard deviations) and the errors Both groups, however, were severely impaired in the psychological tests by the anoxemia, indicating a general loss of sensory motor, and mental alertness The psychological tests reflected the impairment of the circulatory and respiratory mechanisms and the consequent lack of oxygen being delivered to the central nervous system

TABLE 30

PSYCHOLOGICAL TESTS

A = Normal Subjects—B = Psychoneurotics

Tests	Control		18 000 feet	
	Mean	Standard deviation	Mean	Standard deviation
Color naming [1]				
A	59.4	3.9	70.4	5.2
B	69.9	4.1	82.5	5.6
Perseveration [1]				
A—First hour	71.0		64.1	
Second hour	76.3		79.7	
B—First hour	69.1		71.0	—
Second hour	90.4	—	90.1	
Choice reaction [2]				
A	41.22	4.17	45.59	4.67
B	55.65	8.13	65.35	8.90
Pursuit meter [3]				
A—First hour	66.74	5.24	80.16	7.95
Second hour	63.12	4.83	60.73	5.27
B—First hour	78.46	8.57	90.67	14.69
Second hour	66.98	5.40	74.07	6.38
Dotting test [4]				
A	12.87	2.91	12.62	3.11
B	11.44	3.43	9.77	3.39
Code test [1]				
A	128.92	6.84	143.38	8.45
B	176.96	9.45	203.98	9.64

[1] In seconds
[2] In hundredths of a second
[3] Score in amount of deviation
[4] Score in number correct per second

VII Results of the Experiments with Excess Carbon Dioxide (3 0 percent) in the Low Oxygen and Low Pressure Chambers (Parts IV and V)

In this part of the investigation an attempt has been made to study the effects of high concentrations of carbon dioxide in the presence of a deficiency of oxygen in the inspired air As described in the introduction, one of the initial respiratory responses of the organism to low oxygen is a marked increase in the rate and depth of breathing, which tends to upset the equilibrium of the gases in the alveolar air particularly the carbon dioxide Y Henderson (31) and others (28A, 23, 22) have stressed the possibility of counteracting the effects of oxygen want by excess carbon dioxide The value of using mixtures of 7 percent carbon dioxide and 93 percent oxygen in carbon monoxide poisoning and in various clinical disorders, where failure of respiration is an important syndrome, has been fairly well established No thorough studies have been made of the blood gases and psychological changes, however, of normal and excess amounts of carbon dioxide in the presence of a deficiency of oxygen This problem seemed to be of particular relevance in high altitude flying in aviation and in the use of sealed cabins in commercial air transportation

Three different experiments have been carried out relative to the hypothesis that the presence of two to three percent carbon dioxide may stimulate the breathing so as to aid the uptake of oxygen There was the possibility that 3 percent carbon dioxide for 3 to 6 hours might be very uncomfortable and have certain harmful effects Even if there were no advantage in the uptake of oxygen, there was the possibility that the excess carbon dioxide would increase the pulmonary ventilation so that sealed aeroplane cabins could be more easily equipped for operations at high altitude

1 In the experiment at Columbia four subjects, somewhat below average in general physical condition, were tested under the following conditions in the low oxygen chamber first, in approximately 11 percent oxygen (17,000 feet) with 0 5 to 0 8 percent carbon dioxide and second, in 9 to 10 percent oxygen (19 000 to 22,000 feet) with 3 0 percent carbon dioxide During each period a series of psychological tests was administered to each subject Mr H T Edwards collected samples of arterial blood and alveolar air The results of the psychological tests are shown in Tables 31 and 32, and the physiological tests and biochemical determinations in Tables 33 to 36, inclusive

In the psychological tests all of the subjects were significantly impaired in the presence of oxygen lack with a fairly normal concentration of carbon dioxide The mean arterial oxygen saturation dropped to approximately 80 percent, and the partial pressure of oxygen in the alveolar air to 40–45 mm Hg Two of the four subjects had to be removed from the chamber toward the end of the two-hour experimental session and a third developed severe tonic-clonic muscular twitches When the experiments were repeated with 3 0 percent carbon dioxide, even though the oxygen percentages were approximately 2 percent lower, i e 5,000 feet higher, the arterial oxygen saturation remained elevated to approximately 80–85 percent and the partial pressure of oxygen in the alveolar air to 45–50 mm Hg All of the subjects did better in the psychological tests in spite of being approximately 5,000 feet higher (cf Table 31) The subjects were also more comfortable and complained of fewer unpleasant symptoms (cf Table 32)

TABLE 31

PSYCHOLOGICAL TESTS—EXPERIMENT IN LOW OXYGEN AND WITH 3 0 PERCENT CO_2 IN CHAMBER

Condition	Color naming		Code Time in Sec	Memory 10-perfect score
	Time Sec.	Errors		
Berman				
Control	62	1	104	8
11% O_2[1]+0 6% CO_2				
First hour	70	7	141	4
Second hour	72	5	125	5
10% O_2[2]+3 0% CO_2				
First hour	64	3	107	6
Second hour	66	2	126	6
Friedman				
Control	50	2	109	7
11% O_2+0 6% CO_2				
First hour	47	13	118	4
Second hour	59	7	130	3
10% O_2+3 0% CO_2				
First hour	49	4	108	6
Second hour	52	3	112	5
Jerome				
Control	51	2	130	8
11% O_2+0 6% CO_2				
First hour	58	7	175	2
Second hour	60	5	172	2
9% O_2[3]+3 0% CO_2				
First hour	56	2	145	3
Second hour	59	3	141	4
Reichline				
Control	35	2	110	7
11% O_2+0 6% CO_2				
First hour	42	10	160	3
Second hour	48	7	158	2
9% O_2+3 0% CO_2				
First hour	30	7	118	5
Second hour	40	3	120	5

[1] 11 percent oxygen corresponds to approximately 17,000 feet
[2] 10 percent oxygen corresponds to approximately 19,000 feet
[3] 9 percent oxygen corresponds to approximately 22,000 feet

2 The Harvard Experiment was carried out in the low oxygen room at the Fatigue Laboratory More extensive studies were made of the changes in respiration and the blood The experiments also continued over a longer period of time (6 hours) and the concentrations of oxygen and carbon dioxide were more carefully controlled The results of the psychological tests are shown in Tables 37 and 38, and the alveolar oxygen and percent saturation of the arterial blood with oxygen in Table 39 The author is indebted to Dr D B Dill for permission to use the data of Table 39 and for the interpretation of the physiological findings discussed below [8]

[8] For a more complete discussion of these experiments cf Dill, D B, Edwards, H T, and Robinson S, with the collaboration of Armstrong, H G and Helm J W Pulmonary gaseous exchanges at low barometric pressure and in air mixed with nitrogen Jour Aviation Med, Vol 10 March, 1939

The first experiment was a control The four subjects, who were also the four observers (Dill, Edwards, McFarland, and Robinson), ate the same breakfast and were ready to begin observations at 8 30 The room was closed, an absorbing unit for carbon dioxide was started, and a simple cooling device was available The temperature was kept between 20° and 26° C and the humidity between 50 and 70 percent The carbon dioxide absorber provided a comfortable air circulation The carbon dioxide was kept at about 0 6 percent and the oxygen between 20 8 and 21 1 percent. The day was divided into four periods of about 2 hours each In each period a complete set of physiological and psychological studies was made on each individual Four samples of arterial blood were drawn from each man during the day for study of the oxygen uptake, carbon dioxide content, alkaline reserve, and pH Between the second

TABLE 32 —**Physiological and Psychological Complaints**

	12% O_2 Oct 15		12% O_2+3% CO_2, Oct 22		11% O_2+3% CO_2, Nov 5		11% O_2, Dec. 3	
	Yes	No	Yes	No	Yes	No	Yes	No
Circulatory								
Palpitations or cardiac distress	1	3	0	4	1	3	1	3
Respiratory								
Shortness of breath	4	0	4	0	4	0	3	1
Periodic or irregular breathing	2	2	2	2	1	3	3	1
Sighing or long deep breaths	2	2	1	3	3	1	4	0
Digestion								
Nausea or indigestion	3	1	0	4	0	4	3	1
Gas on stomach or in intestines	3	1	1	3	0	4	4	0
Exertion (muscles)								
Impaired coordination or clumsiness	0	4	0	4	2	2	3	1
Easily fatigued on exertion	4	0	3	1	4	0	3	1
Muscular stiffness and cramps	0	4	0	4	0	4	0	4
Tremors—fingers, hands, etc	2	2	1	3	1	3	0	4
Excessive sleepiness	4	0	3	1	4	0	4	0
Stuttering or blocking of speech	0	4	0	4	1	3	0	4
Greater effort to carry out tasks	3	1	1	3	4	0	3	1
Sensory								
Headache	3	1	0	4	1	3	4	0
Visual or auditory impairment	3	1	1	3	0	4	4	0
Ringing or buzzing in ears	0	4	0	4	0	4	0	4
Cold extremities	1	3	0	4	0	4	0	4
Feeling of heat and sweating	0	4	0	4	0	4	1	3
Vertigo or dizziness	2	2	0	4	2	2	4	0
Psychological								
Feel talkative and excited	1	3	0	4	0	4	2	2
Difficulty in concentrating (distractable)	3	1	0	4	2	2	3	1
Slowness in reasoning	2	2	0	4	1	3	4	0
Mentally lazy	4	0	1	3	3	1	3	1
Feel depressed and grouchy	0	4	0	4	0	4	0	4
Feel exhilarated and gay	1	3	0	4	0	4	0	4
Nervous, high strung inward tension	0	4	0	4	0	4	0	4
Sudden changes in mood	0	4	0	4	0	4	0	4
Fidgety or restless	0	4	0	4	0	4	0	4
Worry excessively about health	0	4	0	4	0	4	0	4
Feel indifferent and exhausted	2	2	0	4	1	3	2	2
Total	50	70	18	102	35	85	58	62

and third periods a lunch of soup and crackers was taken

In subsequent experiments the same subjects were used and the same routine followed. In the second experiment the first two-hour period was carried out as before and then carbon dioxide was admitted and maintained for 6 hours at 2.8 to 3.1 percent. In other respects conditions were the same as before. We found that this concentration of carbon dioxide increased the volume of air breathed per minute about 120 percent. However, it did not modify significantly the oxygen uptake under the conditions of this experiment. This does not imply that increased breathing will not modify oxygen uptake under other conditions; this will be discussed below. The increased volume of air used kept the ratio of bicarbonate to free carbonic acid nearly constant; actually the ratio decreased from 20 to 18. This was associated with a decrease in pH from 7.40 to 7.36. The observations were carried on with no discomfort and without well-defined awareness that the atmosphere was abnormal. There were no after effects discernible. The results of the psychological tests were within the normal range of variability. The data for the control experiments and for the tests carried out in 3.0 percent CO_2 and 21 0 percent O_ are not shown in the tables below.

In the third experiment the room was closed after the preliminary observations, nitrogen admitted and enough oxygen was displaced to leave an atmosphere containing about 11.0 percent oxygen. This is roughly equivalent to 17,000 feet, and the ascent was made in stepwise fashion over one hour. Carbon dioxide was absorbed and after a short period of adjustment, during which 11.0 oxygen was reached, that oxygen percentage was main-

TABLE 33.—**Results of the Physiological Tests and Biochemical Determinations**

Subject Berman

Berman	Chamber		Pulse	Blood Pressure		Alveolar air		Arterial blood			
	O_2	CO_2		Sys	Dias	O_2	CO_2	Percent O_2	Percent saturation	Lactic acid	Sugar
Control	20.06	0.04	60	101	53	102.7	36.8	19.7	98	12.6	100
Ascent											
10 minutes			57	106	54						
20 minutes			62	114	68						
30 minutes			64	108	61						
First hour											
10 minutes	11.2	3	61	103	60						
20 minutes			60	101	63	44.8	29.4				
30 minutes	11.1	4	58	105	66						
40 minutes			62	105	60			17.6	80	12.6	104
50 minutes			64	109	55						
60 minutes	11.0	6	64	116	66						
Second hour											
10 minutes	11.3	6	66	108	60						
20 minutes			64	108	60	40.6	37.1				
30 minutes	11.2	7	62	118	61			15.2	71	9.7	106
40 minutes			82	140							
50 minutes			(1)								
60 minutes	11.0	7	( )								
Control	20.96	.04		125	69	102.7	36.8	19.7	98	10.4	106
Ascent											
10 minutes	13.7	1.2	64	132	68						
20 minutes	10.8	4.4	60	135	68						
30 minutes	8.7	3.5	64	125	67						
First hour											
10 minutes			60	115	64						
20 minutes	9.8	3.0	68	113		54.0	43.4				
30 minutes	9.9	3.2	60	108	65						
10 minutes			60	105	65						
50 minutes	10.5	3.5	62	115	70				93	11.2	103
60 minutes			62	116	70						
Second hour											
10 minutes	10.2	3.2	58	113							
20 minutes	10.3	2.4	64	112	70	52.3	40.2				
30 minutes	10.5	3.1	04	105	68						
40 minutes			74	108	68			17.7	85	8.9	109
50 minutes			74	110	75						
60 minutes			76	115	80						

[1] Tremors

tained for six hours As will be seen in Table 39, this reduced the oxygen saturation to 70 percent Expressed in another fashion, the arterial blood contained nearly five times as much unoxygenated hemoglobin as is normally the case The breathing increased about 20 percent above normal, and this had the effect of raising the ratio of bicarbonate to free carbonic acid in the blood from 20 to 22 This is about equal in magnitude, though opposite in sign to the effect of 3 percent carbon dioxide All of the subjects were definitely handicapped during the six hours of this experiment The digestion was retarded, there was some nausea and dizziness, and three had moderate headaches which persisted for an hour or longer after leaving the room All of the subjects were poorer in the psychological tests (cf Tables 37 and 38)

The fourth experiment was devised to test the combined effects of 3 percent carbon dioxide and 11 0 percent oxygen The breathing was greatly increased The oxygen saturation was notably modified by the increased ventilation of the lungs The mean saturation was 90 percent instead of 70 (table 39) In other words, the unoxygenated hemoglobin in arterial blood was only twice normal instead of 5 times normal In the one case the oxygen supply was seriously interfered with, in the other case it was slightly reduced

It is notable in this fourth experiment that the ratio of carbonic acid to bicarbonate remains very nearly constant, in other words, the reaction of the blood remains at its normal value In view of this, and also due to the fact that the oxygen saturation was as high as 90 percent, it is not surprising that none of us felt particularly uncomfortable in this experiment Only one had a headache, it was slight, and disappeared as soon the experiment was over There was reduced appetite and some indiges-

TABLE 34 —**Results of the Physiological Tests and Biochemical Determinations**

Subject Friedman

Friedman	Chamber		Pulse	Blood pressure		Alveolar air		Arterial blood			
	O_2	CO_2		Sys	Dias	O_2	CO_2	Percent O_2	Percent Saturation	Lactic acid	Sugar
Control	20 96	0 04	72	105	62	103 7	40 4	21 0	100	10 4	99
Ascent											
10 minutes			72	93	50						
20 minutes			72	95	51						
30 minutes			73	95	58						
First hour											
10 minutes	11 2	3	82	98	58						
20 minutes			68	100	48						
30 minutes	11 1	4	81	96	60						
40 minutes			80	96	60						
50 minutes			74	95				15 9	85	15 6	109
60 minutes	11 0	6	70	91							
Second hour											
10 minutes	11 3	6	90	88	48						
20 minutes			92/54			41 9	38 8				
30 minutes	11 2	7						17 0	83	14 1	108
40 minutes											
50 minutes											
60 minutes	11 0	7									
Control	20 96	04	76	125	82	103 7	40 4	21 0		11 9	110
Ascent											
10 minutes	13 7	1 2	81	128	76						
20 minutes	10 8	4.4	86	127	78						
30 minutes	8 7	3 5	100	127	78						
First hour											
10 minutes			100	120							
20 minutes	9 8	3 0	90	120		58 9	44.3				
30 minutes	9 9	3 2	84	115							
40 minutes			84	115	60						
50 minutes	10 5	3 5	80	115							
60 minutes			80	115				18.5	85	12.0	115
Second hour											
10 minutes	10 2	3 2	96	115	66						
20 minutes	10 3	2.4	96	115	65	50 6	39 9				
30 minutes	10 5	3 1	94	118	65						
40 minutes			84	115	66						
50 minutes			82					17 8	82	12.6	111
60 minutes			80								

tion in two cases, but all agreed that the experience was less arduous than with low oxygen alone It was our impression that the presence of 3 percent carbon dioxide lowered the altitude from 17,000 to approximately 12,000 feet

3 Through the cooperation of Captain H G Armstrong and Dr J W Heim, these experiments were repeated in the low-pressure chamber at Wright Field, Dayton, Ohio The same experimental procedure was used as in the low-oxygen room at the Fatigue Laboratory and the same individuals (Dill, Edwards, McFarland and Robinson) served as their own experimental subjects The results of the psychological tests are shown in Table 40 and the findings relating to the alveolar oxygen and percent saturation of the arterial blood with oxygen in Table 41

It was our intention to reduce the total pressure to a value equivalent to 17,000 feet On the whole, our subjective experiences and the psychological tests were not unlike those in the low-oxygen chamber at the Fatigue Laboratory Arterial blood samples were drawn and passed through the air lock for analysis Samples of air from the pressure chamber were drawn at intervals during the day, but these were not analyzed until the following day We were astonished to find that the carbon dioxide had been rising and the oxygen falling during the day due to a defect in the ventilating system We had actually been working at 22,000 feet with carbon dioxide equivalent to 2 5 percent It is safe to say that with such a reduction in oxygen taking place without excess carbon dioxide all of us would have been sick or collapsed Two days later when the ventilation was working properly we observed that, aside from the effects on the eardrum of increasing and decreasing pressures the physiological and psychological consequences of a given oxygen pressure were the same whether produced by adding nitrogen to the air at atmospheric pressure or

TABLE 35 —**Results of the Physiological Tests and Biochemical Determinations**

Subject Jerome

Jerome	Chamber		Pulse	Blood pressure		Alveolar air		Arterial blood			
	O_2	CO_2		Sys	Dias	O_2	CO_2	Percent O_2	Percent saturation	Lactic acid	Sugar
Control	20 96	0 04	105	108	64	105 2	38 1	19 1	92	14 1	99
Ascent											
10 minutes			126	114	80						
20 minutes			138	120	78						
30 minutes			114	124	74						
First hour											
10 minutes	11 0	3	130	120	80						
20 minutes			111	122	84	45 2	34 1				
30 minutes	11 3	4	120	120	84						
40 minutes			128	120	84			14 6	71	10 4	109
50 minutes			118	121	63						
60 minutes	11 1	5	120	130	62						
Second hour											
10 minutes	11 2	6	80	118	75						
20 minutes			122	125	72	42 2	31 0				
30 minutes	11 1	7	90	115	76						
40 minutes			77	115	62			14 1	68	14 1	120
50 minutes			116, 66	110	63						
60 minutes	11 0	7		100	68						
Control	20 96	04	90	115	70	105 3	38 1	19 1	92	11 9	113
Ascent											
10 minutes		3 1	88	120	69						
20 minutes		4 2	112	119	71						
30 minutes	8 0	3 3	108	110	70						
First hour											
10 minutes	8 7	3 2	104	112	66						
20 minutes	8 7	3 2	100	120	65	44 2	38 7				
30 minutes	8 7	3 1	112	120	65						
40 minutes			106	121	70			15 0	72	12 6	112
50 minutes			106	112	70						
60 minutes	9 6	3 3	106	112	66						
Second hour											
10 minutes	9 2	2 9	90	112	65						
20 minutes			99	100	70	44 9	38 1				
30 minutes			99	110	70						
40 minutes			112	115	70			15 5	67	12 6	102
50 minutes			108	105	70						
60 minutes			124								

Table 36.—Results of the Physiological Tests and Biochemical Determinations

Subject Reichline

Reichline	Chamber O₂	Chamber CO₂	Pulse	Blood pressure Sys	Blood pressure Dias	Alveolar air O₂	Alveolar air CO₂	Arterial blood Percent O₂	Arterial blood Percent saturation	Arterial blood Lactic acid	Arterial blood Sugar
Control	20.96	0.04	80	101	52	107.2	38.9	20.0	98	10.4	102
Ascent											
10 minutes			87	101	60						
20 minutes			91	101	61						
30 minutes			98	96	60						
First hour											
10 minutes	11.0	3	90	94	60						
20 minutes			90	94	58	43.8	32.1				
30 minutes	11.3	4	96	101	60			17.2	81	15.4	110
40 minutes			90	98	58						
50 minutes			90	92							
60 minutes	11.1	5	94	95	60						
Second hour											
10 minutes	11.2	6	100	90	60						
20 minutes			56			44.0	29.6				
30 minutes	11.1	7						17.4	62	11.9	109
40 minutes											
50 minutes											
60 minutes	11.0	7									
Control	20.96	04	72	110	74	107.2	38.9	20.0	98	11.2	105
Ascent											
10 minutes		3.1	72	108	75						
20 minutes		4.2	72	108	78						
30 minutes	8.0	3.3	72	111	78						
First hour											
10 minutes	8.7	3.2	80	105							
20 minutes	8.7	3.2	80	110		41.9	37.6				
30 minutes	8.7	3.1	76	108				17.2	82	13.4	108
40 minutes			82	105							
50 minutes			82	105							
60 minutes	9.6	3.3	78	112	75						
Second hour											
10 minutes	9.2	2.9	74	105	71						
20 minutes			82	115	70	46.1	33.6				
30 minutes			104	115	68			17.6	80	11.9	125
40 minutes			96	108	68						
50 minutes			90								
60 minutes			90								

Table 37.—Psychological Tests

	Audiometer		Heterophoria (Exo)		Choice reaction time			
	11% O₂+3% CO₂	11% O₂+0.5% CO₂	11% O₂+3% CO₂	11% O₂+0.5% CO₂	11% O₂+3% CO₂ Mean	11% O₂+3% CO₂ Errors	11% O₂+0.5% CO₂ Mean	11% O₂+0.5% CO₂ Errors
Dill								
Control	14	15	4	4	39	0	41	0
2d hour	17	17	6	7	39	1	46	3
3d hour	16	18	5	5	41	2	47	4
4th hour	17		5		37	1		
Edwards								
Control	17	15	2	2	40	1	41	0
2d hour	16	19	2	4	38	1	44	3
3d hour	16	16	2	6	39	0	47	5
4th hour	17		3		42	0		
McFarland								
Control	15	16	3	3	41	0	41	0
2d hour	16	17	6	6	42	1	43	2
3d hour	16	17	5	7	42	0	46	3
4th hour	17		6		43	0		
Robinson								
Control	18	17	5	5	52	0	52	2
2d hour	19	18	7	7	53	0	55	3
3d hour	18	20	6	6	57	0	59	4
4th hour	18		6		52	1		
Average								
Control	16	15.5	3.5	3.5	43.0	3	43.8	5
2d hour	17	17.8	5.3	6.0	43.0	8	47.0	2.8
3d hour	16.5	17.8	4.5	6.0	44.6	5	49.8	4.0
4th hour	17.2		5.0		43.5	5		

TABLE 38.—**Psychological Tests**

	Memory (% correct)		Code (in seconds)			
	11% O + 3% CO_2	11% O_2 + 0.5% CO_2	11% O_2 + 3% CO_2		11% O_2 + 0 % CO	
	Mean	Mean	Mean	Errors	Mean	Errors
Dill						
Control	90	90	117	0	118	1
2d hour	70	60	121	1	124	6
3d hour	60	40	123	0	135	2
4th hour	70		125	0		
Edwards						
Control	80	80	121	0	121	1
2d hour	60	60	122	1	128	5
3d hour	50	30	127	2	134	2
4th hour	50		120	0		
McFarland						
Control	90	80	143	1	127	1
2d hour	70	50	153	1	147	3
3d hour	70	50	151	2	160	2
4th hour	60		143	0		
Robinson						
Control	100	90	151	0	160	1
2d hour	70	60	150	1	165	4
3d hour	60	60	154	1	173	
4th hour	70		150	1		
Average						
Control	90	85	133	.25	129	1.0
2d hour	67.5	65	136.5	1.00	140.5	4.5
3d hour	60	45	138.5	1.25	149.5	1.5
4th hour	62.5		134.5	.25		

by decreasing the total pressure in a low-pressure chamber.

VIII. Results of the Experiments Carried Out During Flights at High Altitude on Commercial Air Transport Planes (Part VI)

During the past summer (1937) an opportunity was afforded through the generosity of the United Air Lines and the Pan American Airways (both companies provided free transportation) to check some of the data reported above under actual flight conditions on their trans-Pacific and transcontinental operations.

1. *Results of experiments on transcontinental flights.*—On June 3, D. B. Dill of Harvard University and F. G. Hall of Duke University made the flight between Newark and Salt Lake City. The average altitude was between 8,000 and 10,000 feet. The flying conditions were fairly good; however, rough air was encountered previous to reaching Denver and Salt Lake City. Both subjects felt quite nauseated on the flight between Denver and Salt Lake City, and just before reaching Salt Lake Dill vomited and Hall would have vomited had he not rested quietly.

On June 21, R. A. McFarland of Columbia University made the flight between Newark and Chicago, and on June 22 from Chicago to Salt Lake City. J. W. M., World War pilot of Portland, Oregon, and an interested passenger served as subject between Chicago and Salt Lake City. The flying conditions were quite bad between Cleveland and Chicago on June 21 on account of rough air and thunderstorms. Similar conditions were encountered between Denver and Salt Lake City on June 22.

On August 11 and 12, R. A. McFarland and H. T. Edwards made the flight between Oakland and New York. The flying conditions were, on the average, good. An attempt was made to get accurate determinations of the alveolar air. Samples of expired air were obtained in sam-

TABLE 39

ALVEOLAR OXYGEN AND PERCENTAGE SATURATION OF THE ARTERIAL BLOOD WITH OXYGEN

Fatigue Laboratory—Low Oxygen Room

Alveolar oxygen in mm. Hg

	November 5, 1936—3% CO_2, 11% O_2			
	Initial	After 1 hr	After 2 hrs	After 4 hrs
Dill	105.5	60.7	57.9	61.0
McFarland	111.5	66.1		58.3
Robinson	104.5	57.2	63.0	63.7
Edwards	103.1	57.1	61.4	66.6
Mean	106.1	60.3	61.1	62.4
	December 3, 1936—0.5% CO_2, 11% O_2			
Dill	103.2	37.8	41.2	
McFarland	106.1	34.3	38.3	
Robinson	109.7	43.5		
Edwards	113.2	40.6		
Mean	108.0	39.0	39.8	

Percentage saturation of arterial blood with oxygen

	November 5, 1936—3% CO_2, 11% O_2			
	Initial	After 1 hr	After 2 hrs	After 4 hrs
Dill	95.1			90.4
McFarland	95.2	90.8	88.4	90.0
Robinson	96.7	87.6	89.8	89.4
Edwards	96.7		86.6	
Mean	95.9	89.4	88.7	90.0
	December 3, 1936—0.5% CO_2, 11% O_2			
Dill		61.4	70.4	
McFarland		73.8	67.8	
Robinson		73.6	([1])	
Edwards		73.4		
Mean	95.9	70.3	69.1	

[1] Experiment discontinued, observer fainted.

pling tubes and analyzed in the standard Haldane gas-analysis apparatus at the Fatigue Laboratory at Harvard

Results—Physiological tests.—The results of the tests for pulse rate and alveolar carbon dioxide made by Dill and Hall are shown in Table 42 There was a slight, yet significant, increase in pulse rate with increasing altitude, with a tendency toward normal values as each flight progressed A comparison of the alveolar carbon dioxide data with that obtained on the Chilean Expedition (cf Figure 9, Chuquicamata—10,000 feet) indicates that there was a close correspondence in these findings

The results of the pulse rate and blood pressure tests (Recording Tycos Sphygmomanometer) obtained by McFarland are shown in Table 43 The changes in both McFarland and the passenger, J W McC, were only slight and, on the average, quite insignificant

Table 40.—Psychological Tests

Wright Field—Low Pressure Chamber

	Choice reaction time: Mean	Choice reaction time: Errors	Code: Mean	Code: Errors	Memory: Mean
	May 11, 1937—20 000 feet (9.6% O_2—2.5% CO_2)				
Dill					
Control	42.0	1	120	2	00
Second hour	46.7	2	131	2	
Third hour	44.6	1	132	1	60
Fourth hour	45.8	3	129	1	50
Edwards					
Control	40.1	1	121	0	80
Second hour	43.2	1	127	5	70
Third hour	44.0	2	158	3	60
Fourth hour	39.9	1	158	1	40
McFarland					
Control	44.0	0	143	1	60
Second hour	49.2	2	153	2	70
Third hour		–	150	0	
Fourth hour	50.4	1	155	2	50
Robinson					
Control	47.0	0	151	1	70
Second hour	46.8	2	160	1	70
Third hour	49.0	2			40
Fourth hour	45.2	4	145	0	50
	May 13, 1937—17 000 feet (11.0% O_2—0.3% CO_2)				
Dill					
Second hour	43.7	4	124	1	
Third hour	46.2	1	118	1	50
Fourth hour	44.3	2	122	1	50
Edwards					
Second hour	40.5	4	107	2	40
Third hour	42.0	2	105	1	60
Fourth hour	45.5	4	130	2	60
McFarland					
Second hour	45.7	2	143	2	60
Third hour	44.1	1	145	0	70
Fourth hour	45.9	1	143	1	80
Robinson					
Second hour	48.2	2	150	0	50
Third hour			157	1	60
Fourth hour	48.3	0	153	3	50

O_2 and CO_2 in Chamber	9.6% O_2 2.5% CO_2		11.0% O_2 0.3% CO_2		9.6% O_2 2.5% CO_2		11.0% O_2 0.3% CO_2		9.6% O_2 2.5% CO_2	11% O_2 0.3% CO_2
Average										
Control	43.3	0.8	43.3	0.8	133.8	1	133.8	1	80	80
Second hour	46.5	1.8	44.5	3.0	142.8	2.5	131	1.3	70	60
Third hour	45.9	1.3	43.8	1.3	146.7	1	131.3	.8	53	57.5
Fourth hour	45.3	2.3	46.0	1.8	146.8	1	137	1.8	47.5	60

Table 41

ALVEOLAR OXYGEN AND PERCENTAGE SATURATION OF THE ARTERIAL BLOOD WITH OXYGEN

Wright Field—Low-Pressure Chamber

Alveolar oxygen in mm Hg

	Sea Level Boston	During second hour	During fourth hour
	May 11 1937 [1]—2.5% CO_2—9.6% O_2		
Dill	105.5	–	40.0
McFarland	111.5	–	39.4
Robinson	104.5	–	53.3
Edwards	103.1		48.0
Mean	106.1	–	45.2
	May 13 1937 [2]—0.3% CO_2—11.0% O_2		
Dill	–	48.7	–
McFarland		–	–
Robinson		53.3	–
Edwards	–	43.0	–
Mean	–	48.3	–

Percentage saturation of arterial blood with oxygen

	Sea Level Boston	During second hour	During fourth hour
	May 11 1937 [1]—2.5% CO_2—9.6% O_2		
Dill	95.1	65.0	62.2
McFarland	95.2	72.0	70.0
Robinson	96.7	73.3	77.4
Edwards	96.7	69.2	69.6
Mean	95.9	69.9	69.8
	May 13, 1937 [2]—0.3% CO_2—11.0% O_2		
Dill	–	–	64.4
McFarland		87.4	84.4
Robinson	–	74.0	76.8
Edwards	–	72.2	71.2
Mean	–	77.9	74.2

[1] During this experiment the carbon dioxide was being increased at the same time the barometric or total pressure was being lowered, so that the percentage of oxygen was equivalent to 20 000 feet altitude (9.6 percent oxygen) and the percentage of carbon dioxide was 2.1 percent)

[2] The barometric pressure was altered so that the percentage of oxygen available corresponded to 17,000 feet altitude (11.0 percent oxygen) The carbon dioxide was held constant at approximately 0.3 percent.

The data obtained by McFarland and Edwards for the alveolar oxygen and carbon dioxide are shown in Table 44. The results are in close agreement with those from the trans-Pacific flights. If one compares these results with those from the Chilean Expedition (Chuquicamata—10,000 feet) (Figure 9) and from trans-Andean flights (Figures 40 and 41) (refs 44), the results also show a close correspondence. The mean pO_2 and pCO_2 at Chuquicamata for ten subjects were 62.4 and 33.9, respectively. On these flights (at 11,000 feet) the mean pO_2 and pCO_2 were 62.1 and 34.5, respectively.

Results—Psychological tests—The psychological tests included (1) heterophoria, or ocular muscle unbalance, (2) light sense for

TABLE 42.—**Flight on United Air Lines Plane—Newark to Salt Lake City—June 3, 1937**

Subjects: Dr D B Dill (age 44) and Dr F G Hall (age 41)

Time	Altitude	Subject	Pulse	Alveolar pCO_2 mm Hg	Heterophoria (10 cms)	Color naming (in seconds)	Code test: In seconds	Code test: Errors	Memory percent (correct)	General sensations
	Sea level	Dill	69		2.0	54	114	0	80	
		Hall	70		5.0	56	130	1	95	
Newark to Cleveland										
9 13 a m	2 800 feet	Dill	72							
		Hall	72							
9 35 a m	8,000 feet. Slightly rough	Dill	71				118	1	80	Dill, slight belching
		Hall	74				135	3	100	
10 a m	10,000 feet	Dill	70		3.0	55				Above clouds Smooth
		Hall	72		7.0	57				
10 10 a m	10 000 feet	Dill	72				116	0	70	Above clouds Smooth
		Hall	72				133	6	90	
10 30 a m	6 000 feet	Dill	68						70	Rough air
		Hall	68						90	
10 55 a m	6,000 feet	Dill	71		2.5		111	0		Rough
		Hall	68		6.0		137	4		
Cleveland to Chicago										
12 30 p m	8 000 feet	Dill		36.2			117	0	80	
		Hall		37.2			131	2	80	
1 10 p m	8 000 feet	Dill	66	43.4	2.5	55	110	0	100	Enjoyed lunch (both)
1 20 p m	8 000 feet	Hall	72	40.4	6.5	59	128	1	90	
Chicago to Denver[1]										
1 30 p m	8 000 feet (1 hr after lunch)	Dill	80	39.8	3.0	51				Smooth air
		Hall	78	30.2	6.0	55				
2 p m	8 000 feet	Dill		40.3						
		Hall		38.8						
3 07 p m	8 000 feet	Dill		42.4						
		Hall		42.4						
		X	X	39.3						
		X	X	41.0						
3 40 p m	11,000 feet	Dill	73		3.0	58	120	0	80	3 40, 3 50 rough Dill slight breathlessness
		Hall	76		7.0	56	135	1	100	
3 50 p m	10 500 feet	Dill	74	37.2						Smooth air
		Hall	77	35.3						
4 20 p m	5 000 feet	Dill	65							Smooth air
		Hall	69							
4 40 p m	6 000 feet	Dill	66							Smooth air
		Hall	70							
5 10 p m	7 000 feet	Dill	71	38.6	2.5	55	116	0	100	
		Hall	71	39.7	7.0	56	145	1	90	
Denver to Salt Lake City										
7 10 p m	10 000 feet	Dill	70	36.6	3.0	55	112	0	60	Rough Dill vomited
		Hall	70	38.0	7.5	60	134	1	70	Hall nauseated
Means—sea level	Sea level	Dill	68.0		2.0	54.0	114.0	0	80.0	
		Hall	70.0		5.0	56.0	130.0	1	95.0	
	6 000–8,000 feet	Dill	70.7	39.7	2.0	53.6	114.6	2	80.0	
		Hall	71.6	39.2	5.4	56.6	135.2	1.0	90.0	
	10,000–11,000 feet	Dill	71.8	36.9	3.0	54.3	116.0	0	76.0	
		Hall	72.4	37.2	7.2	57.3	134.0	1.6	88.0	

[1] Captain B G M Stewardess S and X passengers

During the last half hour the air was very rough. Hall slept through this but awoke with nausea as the Salt Lake Airport was approached. He did not vomit but had nausea for another hour. Dill vomited just as the airport was reached. Within a few minutes after landing he felt well and had no further discomfort. Neither had headaches.

visual intensity—Reeves wedge, (3) color naming—naming 100 colors as rapidly as possible—score in seconds, (4) transliterating 50 code letters against time (in seconds), and (5) memory for paired words In this test the ten pairs of words were exposed for 15 seconds each Immediately following the initial presentation, the first word of each pair is shown to the subject and he is asked to recall the second (score in percent correct)

The results, as shown in Tables 42 and 43, were consistently yet insignificantly lower at the high altitudes during the flights The variations are only slightly greater than the experimental error and the possible effects due to the distractions while in flight In the code test, for example, there was an average decrease in time for each test of 2 to 3 seconds at high altitude compared to sea level, in the memory test, from 4 percent to 8 percent

The amount of unsaturation of the arterial blood with oxygen at 10,000 feet decreases from the normal sea level value of 96 percent to approximately 90 percent At 12,000 feet the percent saturation of the arterial blood would be approximately 86 percent From a wide number of observations at high altitude on mountain expeditions and in simulated high altitude in chambers at sea level, slight yet statistically insignificant changes in sensory or mental functions with this amount of arterial oxygen unsaturation have been observed

It appears that healthy subjects between the ages of 18 and 60 years are only slightly affected at altitudes of 10,000 feet after two to four hours At 12,000 feet to 14,000 feet the average

TABLE 43 —**Flight on United Air Lines Plane—Newark to Salt Lake—June 21 and 22, 1937**

Subjects Dr R A McFarland (age 35) and Passenger J W Mc. (age 49)

Time	Altitude	Subject	Pulse	Blood pressure	Heterophoria (40 cms)	Visual intensity Reeves wedge		Color naming (In seconds)	Code		Memory (Percent correct)	General sensations
						R	L		(In seconds)	Errors		
Newark to Cleveland June 21	Sea level	--	64	110/76	[1] −2 0	8.0	8 3	64	134	1	80	
9 30 a m	6,000 feet climbing higher		66	--	-	--	--	66	141	0	-	Smooth Felt O K
10 10 a m	10 000 feet		72	120/80	−3 0	7 4	7 5	--	----	- -	80	
10 45 a m	10 000 feet		70	- -		-	- -	65	----	--	--	
Cleveland to Chicago												
11 30 a m	3 000 feet	-	80	---	- -	--	-	---	140	0	60	Air very rough Thunder storms Felt nauseated Felt much better at 12 05
12 05 a m	10 000 feet	-	72	110/78	−2 5	7 6	7 5	--	146	2	--	
Chicago to Denver June 22 [2]												
1 10 p m	10 000 feet	- --	68	118/74	−3 0	--	--	67	-	---	80	Felt fine.
2 00 p m	10,000 feet	-	72	125/76	-	7 4	7 8	-	140	0		
3 10 p m	12 000 feet	-	78	120/76	−4 0	6 6	6 8	--	-	--	70	Felt sleepy
4 05 p m	10,000 feet	J W Mc	80	130/70	-	6 5	6 2	--	-	---	-	Felt nauseated
4 40 p m	8,000 feet	--	-	-		-	---	-	144	1	70	Air very rough
Denver to Salt Lake City [3]												
6 15 p m	10,000 feet	--	74	-	−4. 5		---	68	-	---		Air very rough Storms R M nauseated J W M headache Air rough J W M intense headache [5] R M slight headache and quite fatigued
7 10 p m	10,000 feet		78	112/76	-	- -	--	- -	145	1	60	
		J W Mc	84	140/82	--		-		- -	--		
9 40 p m	Hotel Utah	-	68	124/76	--	8 0	8 2	65	140	2	80	
		J W Mc	78	135/80	--	7 2	7 6	--	----	---		
Mean-Sea Level												
R M	Sea level	-	66	120/76	2 0	8 0	8. 25	64. 5	138	1 5	80	
	10 000 [4]	--	73	117/77	3 4	7 25	7 4	66. 6	142. 5	75	75	
J W Mc	Sea level		78	135/80	--	7 2	7 6	-	- --	--	-	
	10 000 [4]	-	82	135/76	-	6 5	6. 2	---	- --		- --	

[1] Minus signs indicate esophoria.
[2] Captain V W V
[3] Captain E D W
[4] Average altitude
[5] Excessive amount of alcohol on the night previous to the flight

TABLE 44

ALVEOLAR AIR SAMPLES FROM TWO PASSENGERS ON FLIGHT BETWEEN OAKLAND AND CLEVELAND

United Air Lines Planes August 12–13 1937

	9,000 feet barometric pressure 539		11 000 feet barometric pressure 509	
	pO_2	pCO_2	pO_2	pCO_2
Edwards				
Left Reno at 3 p m				
Sample taken at 5 05 p m			62 2	35 2
Left Cheyenne at 7 45 a m				
Reached 11 000 feet altitude at 8 a m				
Sample taken at 8 30 a m			60 4	30 3
Left Chicago at 8 30 a m				
Reached 9 000 feet at 9 15 a m				
Sample taken at 9 40 a m	66 7	34 3		
McFarland				
Left Cheyenne at 7 45 a m				
Reached 11,000 feet altitude at 8 a m				
First sample taken at 8 25 a m			62 7	36 6
Second sample taken at 9 15 a m			63 0	35 8
Left Chicago at 8 30 a m				
Reached 9 000 feet at 9 15 a m				
Sample taken at 9 35 a m	61 7	39 8		
Summary (means)				
Edwards	66 7	34 3	61 3	32 8
McFarland	61 7	39 8	62 8	36 2
Average	64 2	37 0	62 1	34 5
Crew average—Pacific Flights	--	--	66 9	35 3

passenger experiences sleepiness and lassitude and if the air is smooth tends to fall asleep If rough air is encountered however, any tendency toward nausea headache, or cardiac distress tends to be accentuated Passengers who have a tendency toward "nervousness" tend to be more susceptible to the ill effects of high altitude, also those who have had little sleep the night before, or excess alcohol

2 *Results of experiments on trans-Pacific flights*—During the month of August 1937 H T Edwards (biochemist at the Harvard Fatigue Laboratory) and R A McFarland carried out a series of studies on the crew and passengers during a routine flight of the Pan American Clipper Ships flying from Alameda California, to Hong Kong China Between Alameda and Manila, P I, the mean altitude was 9,500 feet, the total flying time 122½ hours and the total nautical miles 14 141 A complete account of this study may be obtained in the original article (cf reference 49) The log of the flight is shown in Figure 42

The investigation was concerned with the effects of gradual ascents (1 to 2 hours) to 8 000 to 12 000 feet altitude followed by long flights varying from 8 to 20 hours in length It was made on airmen in good physical condition while carrying out the normal duties

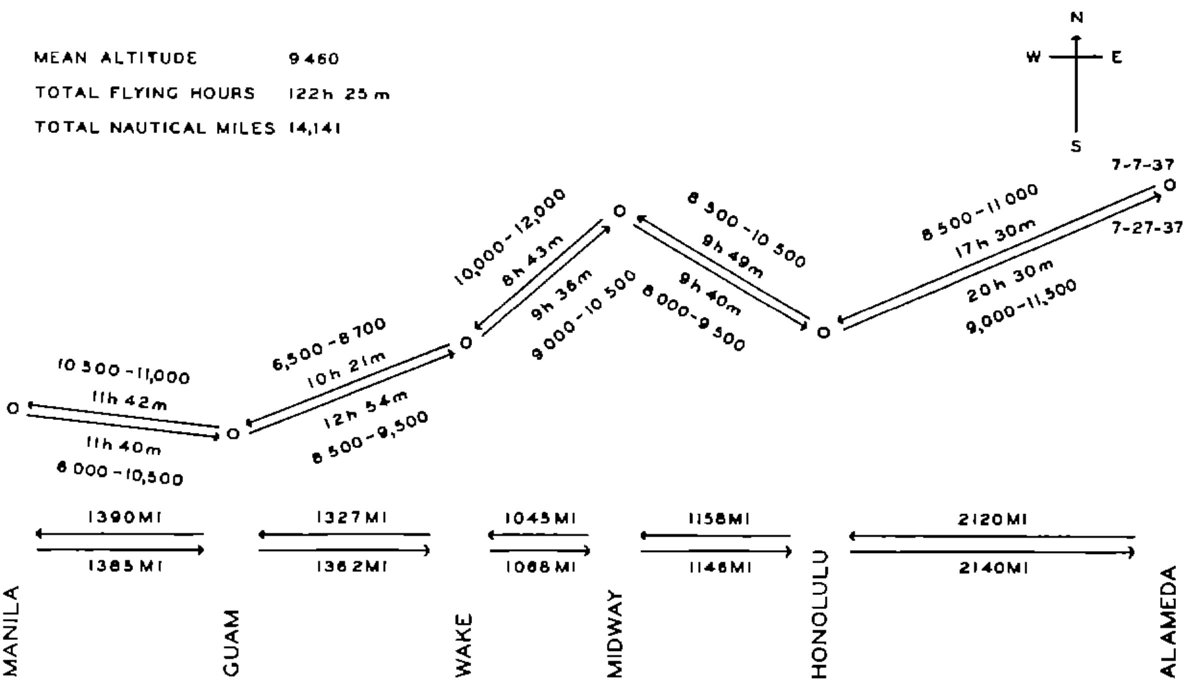


Figure 42—Log of trans-Pacific flight (McFarland)

of operating an aeroplane on trans-Pacific operations, and on passengers The air was relatively smooth throughout the entire flight The investigation was undertaken from the practical point of view of aviation for the following reasons (1) to determine the amount of fatigue involved in long transoceanic flights in terms of objective measurements, (2) to study the maintenance of health in the airmen in carrying out such operations, (3) to analyze the efficiency of the personnel while in flight, and (4) to recommend safety measures in relation to human limitations The study was of general scientific interest from the viewpoint of measuring objectively the changes in the circulation, blood the sense organs, and the central nervous system due to long exposures at moderately high altitudes, as well as in analyzing the amount of acclimatization attained during 122½ hours in the air It also afforded an excellent opportunity to compare the effects of oxygen want under actual flight conditions with studies made on mountain expeditions, and in low-oxygen and low-pressure chambers at sea level

The physiological tests included (1) the Schneider Index, i e, the pulse rate and blood pressure reclining, the changes on standing, the pulse rate after a standard exercise, and the time required for the pulse to return to normal, (2) the minute volume index of the circulation, and (3) the urine volume The biochemical determinations were for oxygen and carbon dioxide in alveolar air, and in blood, the concentration in blood of sugar and lactic acid, and the concentration in plasma of protein, cholesterol, chloride, and nonprotein nitrogen Also, counts were made of red cells and reticulocytes The psychological tests included (1) heterophoria, (2) near point of accommodation, (3) brightness discrimination, (4) quickness of apprehending the meaning of words exposed for fractions of a second in a focal plane shutter apparatus, (5) code test for maintenance of attention and accuracy of transliterating letters, and (6) memory

Results of the psychological tests—In selecting the psychological tests it was necessary to obtain those that could be repeated without marked practice effects, that were sensitive enough to measure slight alterations in functions, that included a fairly wide range of sensory and mental reactions, and that were portable and easy to administer Visual tests were stressed because of the primary importance of that particular sense in flying With the above considerations in mind, the following tests were administered in Alameda and at various intervals throughout the flight The results are shown in Table 45 On the average, there was an impairment of 6 to 8 percent in the psychological tests at 9,000 to 12,000 feet following slow ascents

TABLE 45

PSYCHOLOGICAL TESTS—TRANS-PACIFIC FLIGHTS

[Means and Standard Deviations of Sensory and Mental Tests for Six Airmen and Two Passengers after Five to Six Hours at the Altitudes Indicated]

Test	Midway to Wake 11–12,000 feet, 7/10	Guam to Manila 11,000 feet 7/13	Guam to Wake 9–10,000 feet 7/18	Honolulu (sea level), end of flight, 7/19	Honolulu (sea level) end of lay-over 7/26
Exophoria (prism diopters)					
Mean	1 56	1 94	1 82	0 79	0 75
S D	1 07	1 53	1 00	52	77
P P of accommodation (c m)[1] (right eye)					
Mean	14 07	14 00	13 78	13 57	13 17
S D	3 81	3 50	3 90	3 25	3 10
Brightness Discrimination[1] (right eye)					
Mean	[2] 7 7	[2] 7 6	[2] 7 9	8 8	8 8
S D	31	27	27	34	00
Speed of apprehension (1/90 sec), one word series					
Mean (percent correct)	91 1	94 0	90 4	93 7	92 3
S D	8 44	3 46	5 95	8 45	8 12
Two-word series					
Mean (percent correct)	60 8	65 0	60 0	68 6	69 3
S D	12 05	9 93	9 67	13 0	12 76
Johnson Code (seconds)					
Mean	134 0	132 1	132 0	125 4	123 7
S D	8 53	12 06	8 18	6 71	9 25
Memory test (percent correct)					
Mean	76 71	74 29	73 57	85 00	88 33
S D	12 38	10 12	14 69	6 55	5 60

[1] Results were similar for the left eye

[2] These means represent statistically significant differences from the observed value at end of flight, i e less than 1 chance in 100 that chance variation could have accounted for this value None of the other differences were reliable statistically

Results of biochemical tests—In an attempt to discover whether there was a significant alteration in the respiratory response of the airmen to the long flights at high altitudes, and consequently marked variations in the blood gases, an analysis was made of the alveolar air and the percent saturation of the arterial blood The following conclusions may be drawn from these tests

Alveolar air.—The average partial pressure of oxygen and of carbon dioxide, expressed in mm Hg, is normal for the 11,000 feet altitude (cf Table 46). The mean partial pressure of oxygen in these airmen averaged 4.8 mm higher than that of unacclimatized passengers after an ascent to the same altitude in 45 minutes and that of subjects transported by aeroplane to similar altitudes within one half an hour by Schneider and Clark (56). The similarity of the averages for the crew and for acclimatized men at this altitude suggests that the airmen become adapted to the high altitude and maintain a higher oxygen partial pressure than passengers. Thus, the added burden on the crew of flying the ship has no impairing effect on the respiratory mechanism.

Arterial blood.—Five arterial bloods and one venous blood were obtained at approximately the time of obtaining the above alveolar air samples on the flight between Honolulu and Alameda (after 12 hours at 11,000 feet). (Cf Table 46.) The average oxygen saturation of the arterial blod (90.1 percent) is close to that found in closed chambers at sea level after several hours and on mountains after acclimatization at this altitude. Lactic acid values of these bloods were within the normal range, with the possible exception of Jr. Pilot (R) (24.2 mgs percent).

Venous blood.—Six venous bloods were drawn after flying for seven hours at 8,000 feet between Midway and Honolulu. The results of the various determinations relating to the blood morphology and blood chemistry are shown in Table 47. The increase in red cells was approximately 10 percent. The normal reticulated count means that no unusual number of immature red cells had entered the blood stream and suggests that the increase is due to the addition of stored cells or to dehydration. The increase in serum protein and serum chloride is also suggestive of a certain amount of dehydration. The normal nonprotein nitrogen, blood sugar and cholesterol values suggest that there was no serious upset of the protein, carbohydrate, or fat metabolism.

TABLE 46.—**Alveolar Air and Biochemical Determinations on Arterial Blood**

Flight Honolulu to Alameda 11,000 feet (509 mm Hg) for 12 hours—Crew No. 2

	Alveolar air		Arterial blood				
	pO_2 (mm)	pCO_2 (mm)	Lactic acid (mgs per cent)	Content O_2 (vols per cent)	Content CO_2 (vols per cent)	O_2 Capacity (vols per cent)	Per cent Sat
Radio (B)	78.0	29.7	14.0	18.14	39.8	20.42	88.8
Navigator (K)	74.0	33.0			41.5	23.35	90.2
Engineer (L)	65.8	40.5	9.7	18.44	44.3	19.91	92.6
Jr. Pilot (P)	67.4	33.0		21.44	38.4	23.01	91.2
Jr. Pilot (R)	69.9	38.4	24.2	(1)		19.16	
Passenger (M)	55.2	37.6	17.5	18.77	42.5	21.40	87.7
Average	66.9	35.3	16.3		41.1	21.2	90.1
Acclimatized man at this altitude	65.0	33.0	15.0		43.0	21.0	88–90

[1] Venous blood.

TABLE 47.—**Biochemical and Morphological Determinations on Venous Blood**

Flight Midway to Honolulu altitude 8,000 feet for 7 hours

	During flight									After 6 days at Honolulu		
	Retic count (per cent)	RBC count (mill.)	Cell vol (per cent)	Size Vc/RBC	Plasma protein (per cent)	Non protein nitrogen (mg per cent)	Blood sugar (mg per cent)	Cholesterol plasma (mg per cent)	Chloride plasma (not under oil) (mg per cent)	RBC count (mill.)	Cell vol (per cent)	Size Vc/RBC
Engineer (A)	1.0	5.55	46.2	0.83	7.56	30.6	90	206	108.7	5.06	46.5	0.92
Jr. Pilot (C)	3	6.00	51.2	85	7.08	20.4	118	217	110.2	5.05	49.9	99
Jr. Pilot (G)	4	5.75	48.0	83	7.24	29.7	108	207	107.1	Left		
Steward (H)	6	5.45			7.38	39.5	87		111.6	Left		
Navigator (L)	7	5.35	45.8	86	7.73	33.0	90	178	110.5	4.75	44.1	93
Jr. Pilot (O)	5	5.00	47.7	91	7.53	31.6	100	225	108.7	5.15	47.5	92
Average	6	5.53	47.8	86	7.52	32.3	99	217	109.4	5.00	47.0	94
Normal	5	5.00 ±0.5	45.0	90	7.00	25–35	90–110	200	105	5.00	45.0	90

With accentuated emotional excitement or worry, the increased secretion of adrenalin may cause a rise in blood sugar The normal values observed in these airmen suggest that no such excitement or worry was taking place

In general, the 17 airmen studied during typical trans-Pacific operations became acclimatized to the high altitude and maintained a high degree of mental and physical efficiency throughout the flight The 11 passengers of average age and fitness studied, although not manifesting the same degree of acclimatization as the airmen, showed no objective signs of fatigue or physical distress It should be kept in mind, however, that the *subjective* feelings of fatigue were fairly acute in both the airmen and passengers at the end of the longer flights although the results from the physiological and psychological tests were, on the average, negative This study indicates that the stress of flying on these trans-Pacific operations is not acute enough to deplete the fuel reserves of the body or give rise to the accumulation of fatigue substances in the blood

IX Summary of the Various Experiments

Before attempting to outline tentative conclusions, a general summary will be given of the entire investigation *First*, the various problems relating to passenger comfort in modern air transportation were outlined It was pointed out that one of the most important questions which has not been solved adequately by the aircraft engineers relates to the effects of the reduced oxygen pressure encountered at high altitudes

Second, the physical factors of the environment at high altitude were discussed in relation to their reaction on the human organism and the amount of oxygen in the inspired air which would be required to maintain sea level conditions (159 mm Hg)

Third, a description was given of the various experimental procedures used at sea level to simulate the essential conditions of high altitude, such as Douglas bags and rebreathing devices, low oxygen and low pressure chambers

Fourth, an analysis was made of the important variables of flying at high altitude, such as the height attained, the length of exposure, the rate of ascent, the physical characteristics of the individual, and the roughness of the air while in flight

Fifth, the physiological mechanisms of acclimatization, with special regard for the importance of carbon dioxide, were analyzed Also, the response of the average unacclimatized passenger was compared with the average acclimatized airman

Sixth, a description of the various experiments was then given, along with the presentation of the experimental data More than 237 subjects were studied during rapid ascents and 84 during slow ascents in the parts of the investigation sponsored by the Bureau of Air Commerce The experiments were divided into six parts, as follows

Part I—In the major experiment there were two rates of ascent, approximately 20 minutes, and 1 hour and 20 minutes to simulated altitudes of 10,000, 12,000, 14,000, 16,000, 18,000, and 21,000 feet A series of physiological and psychological tests was given to each subject before and during each ascent The data was treated by the usual statistical procedures to determine the reliability of the observed differences

Part II—In this experiment the variable of age was partialed out for special study Three age groups (17 to 30 years, 30 to 45 years, and 45 to 72 years) were given the various psychological and physiological tests during rapid and slow ascents to simulated altitudes of 14,000 feet

Part III—The relationship between tolerance for altitude and physical fitness was analyzed in this part of the investigation A group of physically "fit" and physically "unfit" college students was studied during rapid and slow ascents to simulated altitudes of 16,000 feet and during rapid ascents to 12,000 feet Also, a group of patients diagnosed as psychoneurotic, with prominent symptoms of fatigue and exhaustion, was studied during rapid ascents to simulated altitudes of 18,000 feet

Parts IV and V—(Sponsored independently by the Bureau of Air Commerce) An attempt was made to analyze the effects of reduced oxygen pressure with and without an excess amount of carbon dioxide (3 0 percent) in the inspired air The experiments were made under three different experimental procedures (1) low-oxygen room at the Harvard Fatigue Laboratory, (2) low-oxygen chamber at Columbia University, and (3) low-pressure chamber at Wright Field, Dayton, Ohio

Part VI—The final aspect of the investigation dealt with the attempt to check the data obtained at simulated altitudes in chambers at sea level under actual flight conditions at high altitude on commercial air transports These studies were carried out during regular passenger flights on transcontinental (United Air Lines) and trans-Pacific (Pan American Airways) operations

X Conclusions

The following tentative conclusions may be stated concerning the effects of reduced oxygen pressure on man from these experiments, as well as from a review of the literature on the subject These findings will be discussed under the following general headings 1 The specific altitudes where the organism is first affected and where there is a measurable degree of impairment 2 The effects of altitude in relation to rate of ascent 3 The cumulative effects of high altitude, that is, the length of exposure in relation to deterioration or, on the other hand, to acclimatization 4 The way in which the physical characteristics of the individual may influence the response of the organism to high altitude, especially age, physical fitness, emotional excitement or psychoneurotic behavior, and alcohol 5 The role of carbon dioxide in facilitating adaptation, and 6 Interpretation of the possible ways in which a reduction in oxygen pressure may effect cellular activity and bring about an alteration in physiological and mental functioning

1 *The Specific Altitudes Where the Organism Is First Affected and Where There is a Measurable Degree of Impairment*—The maintenance of an adequate oxygen supply in the blood is such an important factor for all cellular activity that changes in the organism apparently take place as soon as one leaves the ground in an aeroplane If one examines the oxygen dissociation curve in relation to the partial pressure of oxygen in the alveolar air and the barometric pressure, it is obvious that alterations would naturally take place at very low altitudes (cf Figure 9)

In a series of experiments on pilots during the World War, Schneider (55) found that the pulse rate per minute was accelerated in a few men at 17 5 percent oxygen (5,000 feet) In one group of 70 men the accelerations began as follows

1 percent began to react between 7,000 and 8,000 ft—16 0–15 5 percent O_2

12 percent began to react between 8,000 and 9,000 ft—15 5–14 9 percent O_2

20 percent began to react between 9,000 and 10 000 ft—14 9–14 2 percent O_2

14 percent began to react between 10,000 and 11,000 ft—14 2–13 7 percent O_2

23 percent began to react between 11,000 and 12,000 ft—13 7–13 2 percent O_2

20 percent began to react between 12,000 and 13,000 ft—13 2–12 7 percent O_2

6 percent began to react between 13,000 and 14,000 ft—12 7–12 2 percent O_2

There is little evidence, however, that a slight reduction in oxygen pressure, giving rise to various compensatory mechanisms such as an initial increase in circulation in hemoglobin, or in pulmonary ventilation, is necessarily harmful to the organism, especially if the person is not ill It is also well known that frequent exercise of one's adaptive mechanisms may, on the other hand, be beneficial The most important question therefore, is not where the very first effects of altitude are manifested but where the alterations may be accentuated enough to actually impair one's sensory and mental functions or bring about physical symptoms of unpleasantness, such as, headaches, vertigo, excessive sleepiness, and fatigue or exhaustion

In the series of studies reported above on large groups of unacclimatized subjects, corresponding to an average cross section of the flying public, the first impairment on psychological functions which proved to be statistically significant was, on the average, in the neighborhood of 12,000 feet (The scattering of the means around the central tendency, however, was fairly large (cf Figures 28 and 31)) This applies to the effects of a reduction in oxygen pressure (under simulated conditions of high altitudes) while the subject was comfortably seated in the chamber and completely unaware of the extent of the alteration in oxygen supply Cf Tables 12 to 15 inclusive The only psychological test which showed statistical reliability at 10,000 feet compared with the control was the one for immediate memory following a rapid ascent Since the means in this test were not significantly different from the control at 12,000 feet, both for the rapid and slow ascents, too much importance cannot be attached to the above finding In general it may be concluded that the average impairment in the most sensitive and reliable psychological tests approximates 6–10 percent at 12,000 feet whether the oxygen pressure is reduced within one-half hour or 4 hours, in a chamber at sea level or in flights at high altitude

The physiological effects are also, on the average, significantly different from the control data in the neighborhood of 12,000 feet cf Tables 8 to 11 inclusive The initial increase in pulse rate was significant at 12,000 feet following rapid ascents, but not at 10,000 feet The findings on the systolic and diastolic blood pressure are difficult to interpret since many subjects show an increase and others a decrease, the net result being that the changes in the means are only slight until the more acute stages of oxygen want are reached

Considered from the point of view of feelings of bodily discomfort, or in terms of physiological and psychological complaints (cf Table 16), the average unacclimatized passenger is significantly affected at 12,000 feet (cf Tables 16 to 18 inclusive, also Table 23) A certain number of subjects are affected at 10,000 feet, but if one considers all of the variables, such as the numbers who might have a headache from doing the tests in normal air, etc , 12,000 feet appears to be the more critical altitude This applies to the complaints mentioned voluntarily, as well as, in answer to the questions in Table 16, for normal subjects while seated in a chamber or in flight at high altitudes

The results of other studies dealing with the psychological effects of lowered oxygen pressure are in general agreement with the findings of this investigation In an experiment with a Douglas bag, for example, Bills (9) found that at 15 percent (8,000 ft) oxygen the number of "blocks" (indicating mental fatigue) was insignificant, but that at 12 percent (or approximately 14,000 ft) there was a significant degree of blocking (cf Figure 43a) In experiments on handwriting with a modified rebreathing apparatus Goralewski (26) found that the initial effects in a handwriting test were apparent in 44 5 percent of his subjects at 18–14 percent O_2 (cf Part A, Figure 43a), and significantly advanced in 52 9 percent subjects at 14–10 percent O_2 (13,000 to 22,000 ft) (cf Part B, Figure 43) In a series of psychological tests, McFarland observed that the initial effects were apparent in the neighborhood of 12,000 feet (45, 48) As shown in Figure 44, the deterioration of motor control in handwriting is progressive with increasing altitude (45) Also Tanaka (64), as clearly illustrated in Figure 45, found that increasing and decreasing the oxygen pressure in Haldane s low-pressure chamber at Oxford significantly altered the average subject's responses on psychological tests in the neighborhood of simulated altitudes of 12,000 feet Other psychological studies which tend to support this general conclusion of 12,000 feet as being the critical turning point are as follows Lowson, low oxygen chamber (41), Jongbloed, low pressure chamber (35), Barach, McFarland, and Seitz, low oxygen chamber (3), Wespi, low pressure chamber (67), Loewy, mountain expeditions (40) Stern observed differences at 8,000 feet in the Alps (62, 63), and McFarland, high altitude flights following rapid ascents (44), and McFarland and Edwards high altitude flights following slow ascent (49) In airmen who are well acclimatized to high-altitude flying the psychological effects are hardly apparent at 12,000 feet (49) During the Chilean Expedition (1935) ten men, between the ages of 29 to 44 years, who became acclimatized to high altitudes over a period of three months were not significantly impaired in a series of sensory, motor, and mental tests until altitudes as high as 15 440 feet, and 17 500 feet, indicated that acclimatization is an important variable cf Figures 46 and 47 (ref 44)

2 *The Effects of Altitude in Relation to Rate of Ascent* —The results of this investigation indicate that rate of ascent is an important variable at 10 000 feet and above i e, if the average subject is transported to simulated altitudes of 10,000 feet and above within 15–30 minutes the

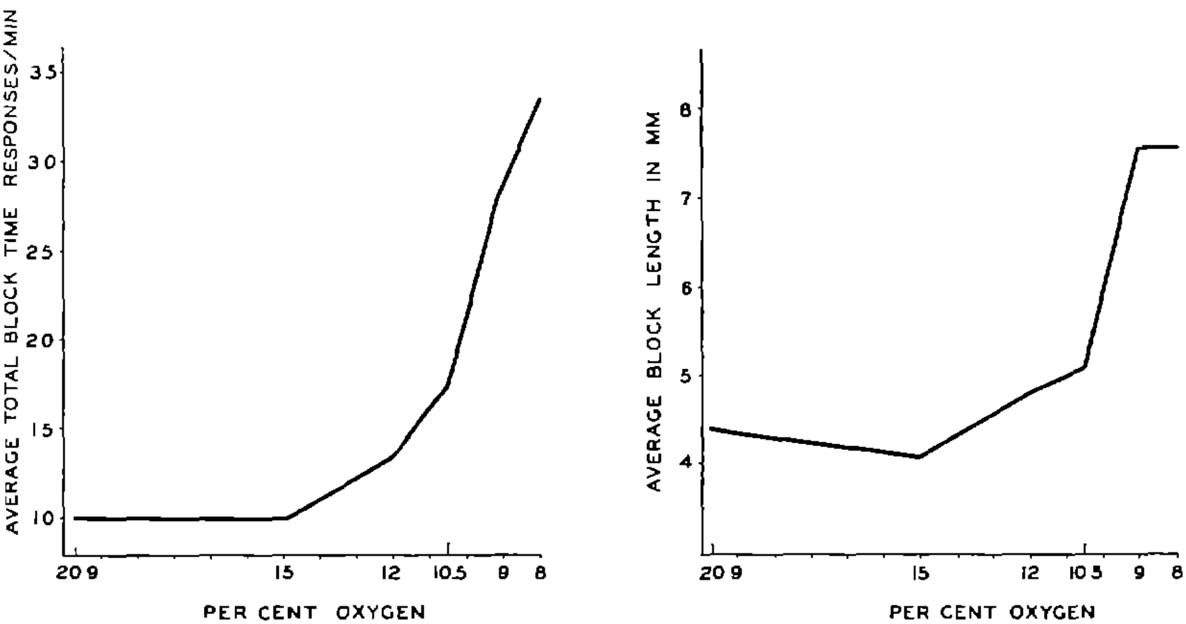


Figure 43a.—Color naming test (Bills)

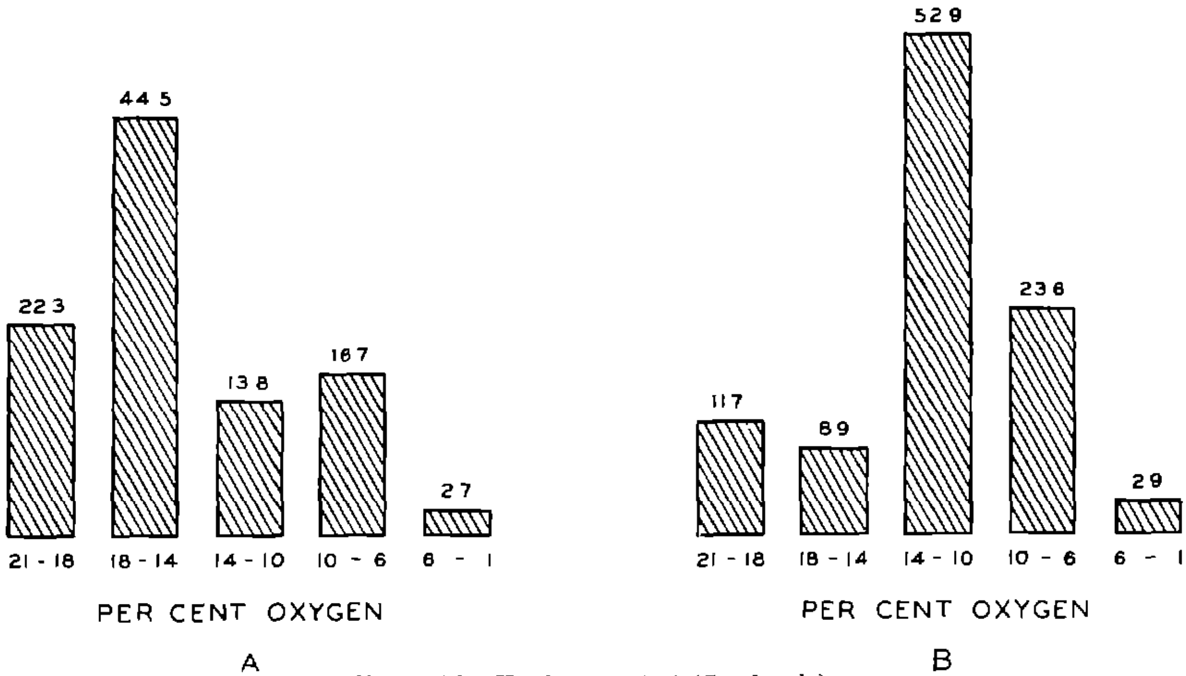


Figure 43b —Handwriting test (Goralewski)

effects of the altitude are, on the average, significantly greater than when similar altitudes are attained within one hour and thirty minutes This appears to be true of the physiological responses as well as the psychological ones

In regard to the physiological tests, the partial pressure of the alveolar oxygen was significantly higher and the carbon dioxide lower in the acclimatized members of the Chilean Expedition compared with the subjects of this experiment (cf Figure 19), also the partial pressure of the alveolar oxygen in the alveolar air was higher in the airmen contrasted with the passengers on the trans-Pacific flights (cf Table 46 (49)) Likewise, in these experiments in simulated high altitudes the partial pressure of the alveolar oxygen was higher following slow ascents than following rapid ascents (Figure 19)

In general it may be said that the variations in pulse rates were less extreme, particularly at

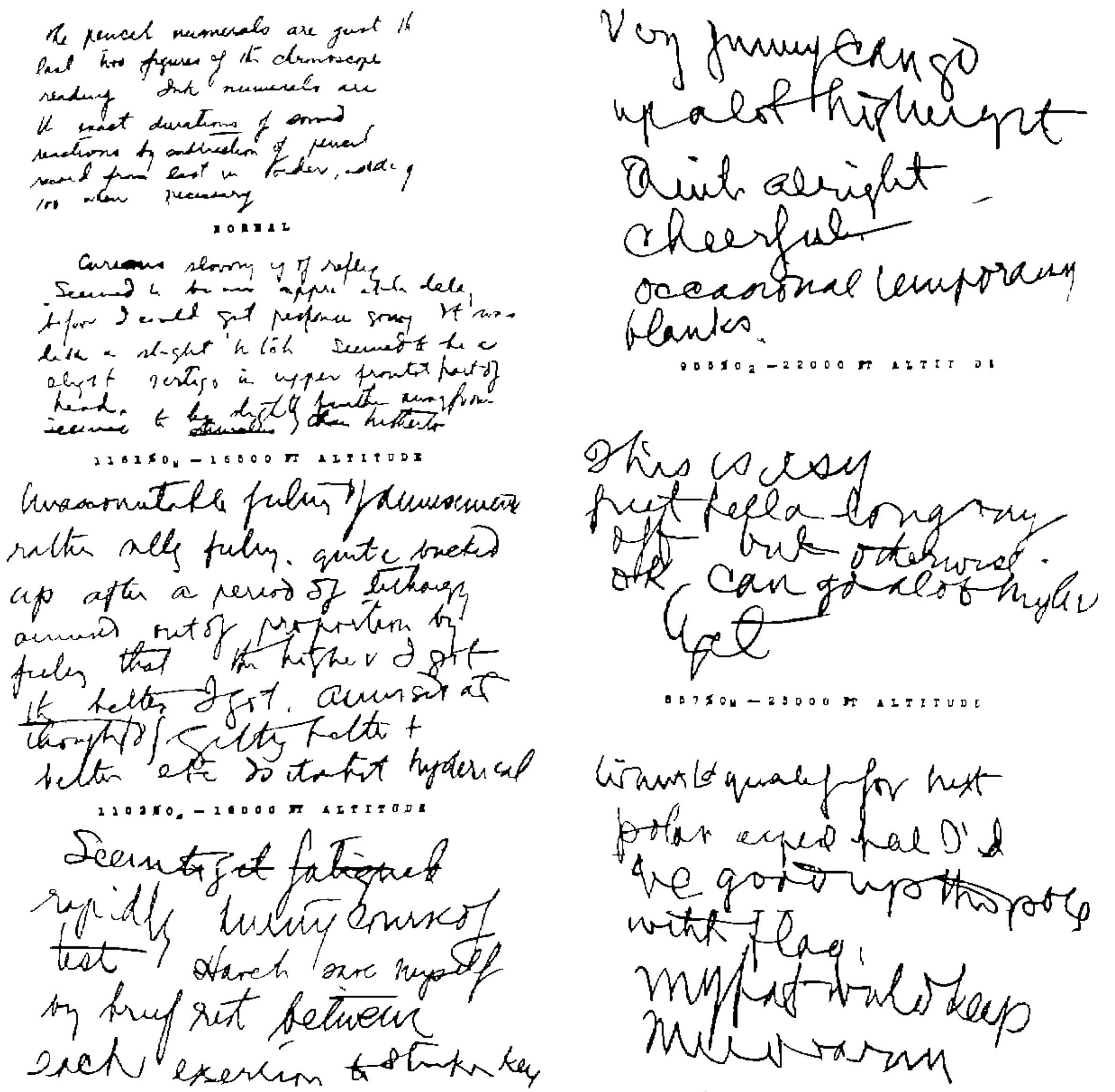


Figure 44.—Handwriting tests at various altitudes (McFarland)

14,000 feet and above following slow ascents than following rapid ones. This may be verified by observing in the tables that the significance of the observed differences was greater for each altitude following rapid ascents than following slow ones (cf. Figures 16 and 18). In physically unfit subjects these differences were quite marked. At 14,000 feet and 16,000 feet, for example, a number of subjects collapsed during rapid ascents, while they became fairly well acclimatized during slow ascents to similar altitudes. The physiological and psychological complaints were also less numerous during slow ascents as contrasted to rapid ones. The greater frequency of complaints during a rapid ascent to 16,000 feet contrasted with a slow one is clearly demonstrated in Table 23 and in Figure 33.

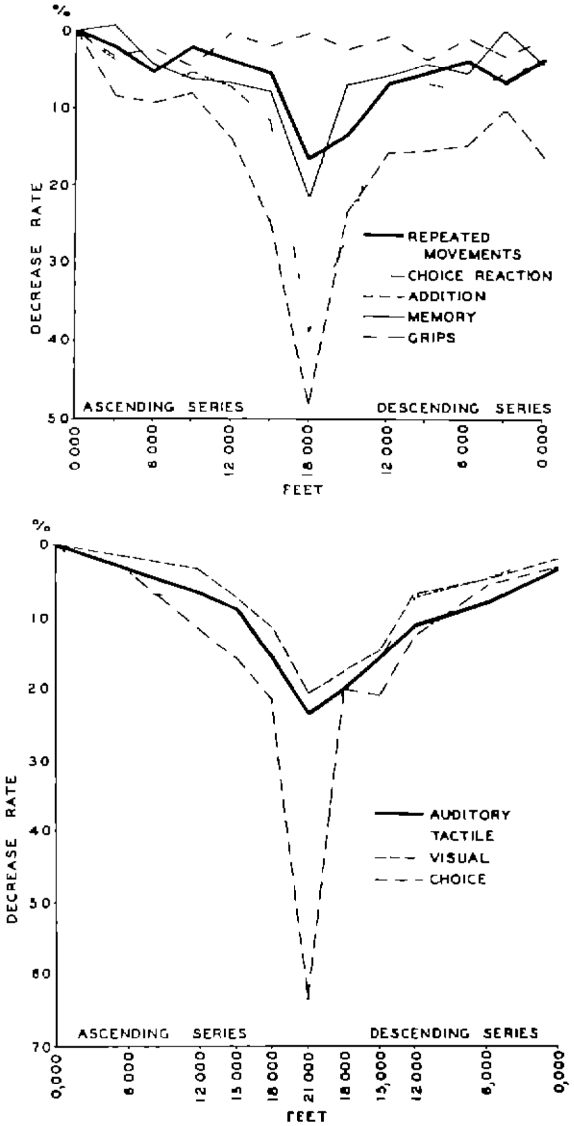


Figure 45.—Psychological tests in low pressure chamber (Tanaka)

Rate of ascent appeared to be a significant factor in success with the various psychological tests at 12,000 feet and above. This general observation may be verified in the case of each test by referring to the relative degree of impairment in the rapid and slow ascents, particularly of the statistical significance of their differences (cf. Tables 12 to 15, inclusive). These differences are very striking in certain of the psychological tests at 16,000 feet (cf. Table 20), particularly in the "unfit" group contrasted to the physically "fit" group.

These findings relative to rate of ascent have been verified by Graff[9] in Germany in a study with animals (mice) at critical altitudes in a low-pressure chamber. He found that the critical level of 12,000 meters at an ascent of 1,000 meters per minute was displaced upward if the pressure was lowered slowly. Armstrong and Heim,[10] on the other hand, in similar experiments at critical altitudes (33,000 feet) observed that with rabbits the faster the rate of ascent the higher the altitude tolerance. These experiments with animals at critical altitudes between 30,000 to 38,000 feet, however, are not directly applicable to the responses of human subjects to moderate altitudes of 12,000 to 18,000 feet. In this investigation under simulated altitudes of 10,000 to 18,000 feet, as well as under actual flight conditions to moderate altitudes, both passengers and airmen appeared to acclimatize more successfully during slow ascents (49).

3. *The Cumulative Effects of High Altitude, i. e., the Length of Exposure in Relation to Deterioration, or, on the Other Hand, to Acclimatization.*—It is quite difficult to draw conclusions from the evidence which is available dealing with the cumulative effects of reduced oxygen

[9] Graff, W. D. Altitude stability as dependent upon rate of ascent in animal experiments. Luftfahrtmed. 1: 351–354, 1937.

[10] Armstrong, H. C., and Heim, J. W. Factors influencing altitude tolerance during short exposures to decreased barometric pressures. Jr. Aviation Medicine 9: 45–56, 1938.

pressure The problem is complicated by the fact that at moderate altitudes of 8,000 to 12,000 feet one may continue to improve during exposures of 10 to 12 hours' duration due to the mechanisms of acclimatization, while at high altitudes of 15,000 to 18,000 feet, over similar periods of exposure, the mechanisms of acclimatization may be inadequate to compensate for the oxygen lack and consequently deterioration may set in after an hour or longer From the experiments which are available thus far, the evidence seems to indicate that the average person can become acclimatized to 8,000 to 12,000 feet while seated quietly in an aeroplane (or in a chamber at sea level) for 6 to 12 hours, while exactly the opposite is true at 16,000 to 18,000 feet Several experiments may be mentioned to support this view

During the trans-Pacific flights the passengers and airmen maintained a high degree of mental and physical efficiency, i e, there were no measurable signs of cumulative deterioration (49) On the other hand, two of the same subjects in both experiments manifested objective signs of deterioration rather than acclimatization after six hours at 17,000 feet in the low-oxygen chamber at the Harvard Fatigue Laboratory and also after 4 hours in the low-pressure chamber at Wright Field Just as Barcroft was showing marked signs of deterioration following his six-day sojourn in the low-oxygen chamber at simulated altitudes of 18,000 feet, so were the subjects in the low-oxygen room at the Fatigue Laboratory quite uncomfortable after six hours at 17,000 feet As mentioned above, one physician collapsed after four hours and a second one was markedly affected after 6 hours at a similar altitude, not regaining complete rationality for some hours following the experiment In the Andes and in other mountainous regions thousands of persons became acclimatized to altitudes of 8,000 to 14,000 feet, and, as observed by the Chilean Expedition, over 150 miners, many of them from the lowlands, were able to become acclimatized so as to live at 17,500 and work at 19,000 feet These miners, however, were unable to live permanently at the mine at 19,000 feet since they were unable to sleep and soon showed marked signs of deterioration (38, 44) Likewise, on the expeditions to the Himalayas the climbers have found that although they can live for a number of weeks or months above 20,000 feet, definite signs of deterioration are manifested sooner or later, and they are forced to return to lower altitudes

A diagram showing the effects of altitude in relation to length of exposure has been drawn in

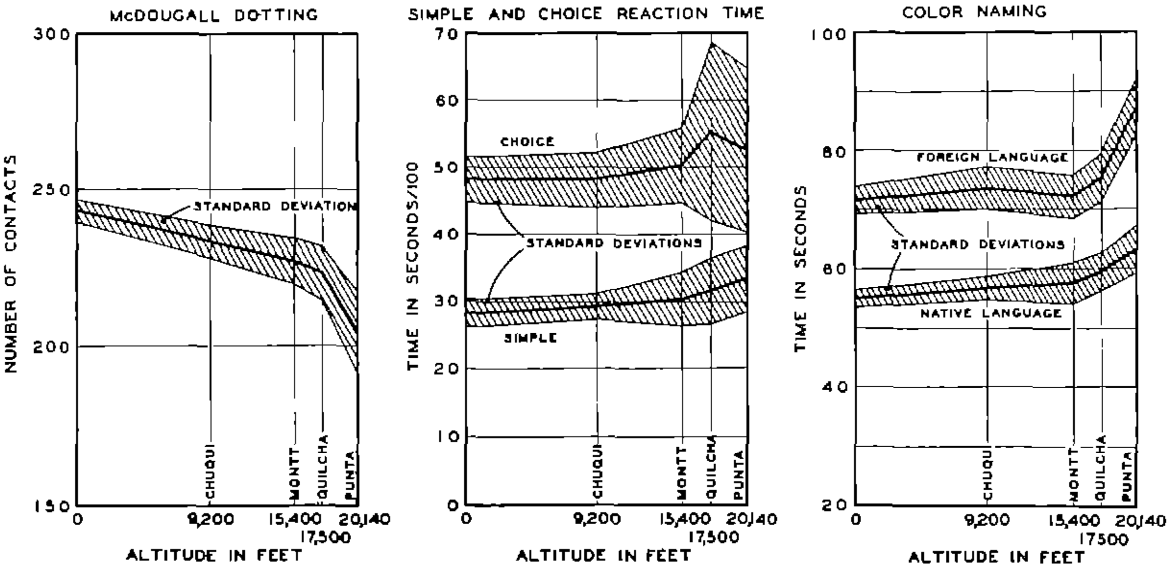


Figure 46 —Effects of altitude on sensory and motor functions (Chilean Expedition, McFarland)

Figure 48 based upon the limited amount of experimental data available It should be kept in mind that these curves are very approximate

4 *The Way in Which the Physical Characteristics of the Individual May Influence the Response of the Organism to High Altitude, Especially Age, Physical Fitness, Emotional Excitement, or Psychoneurotic Behavior and Alcohol* —

AGE —The experiments reported above dealing

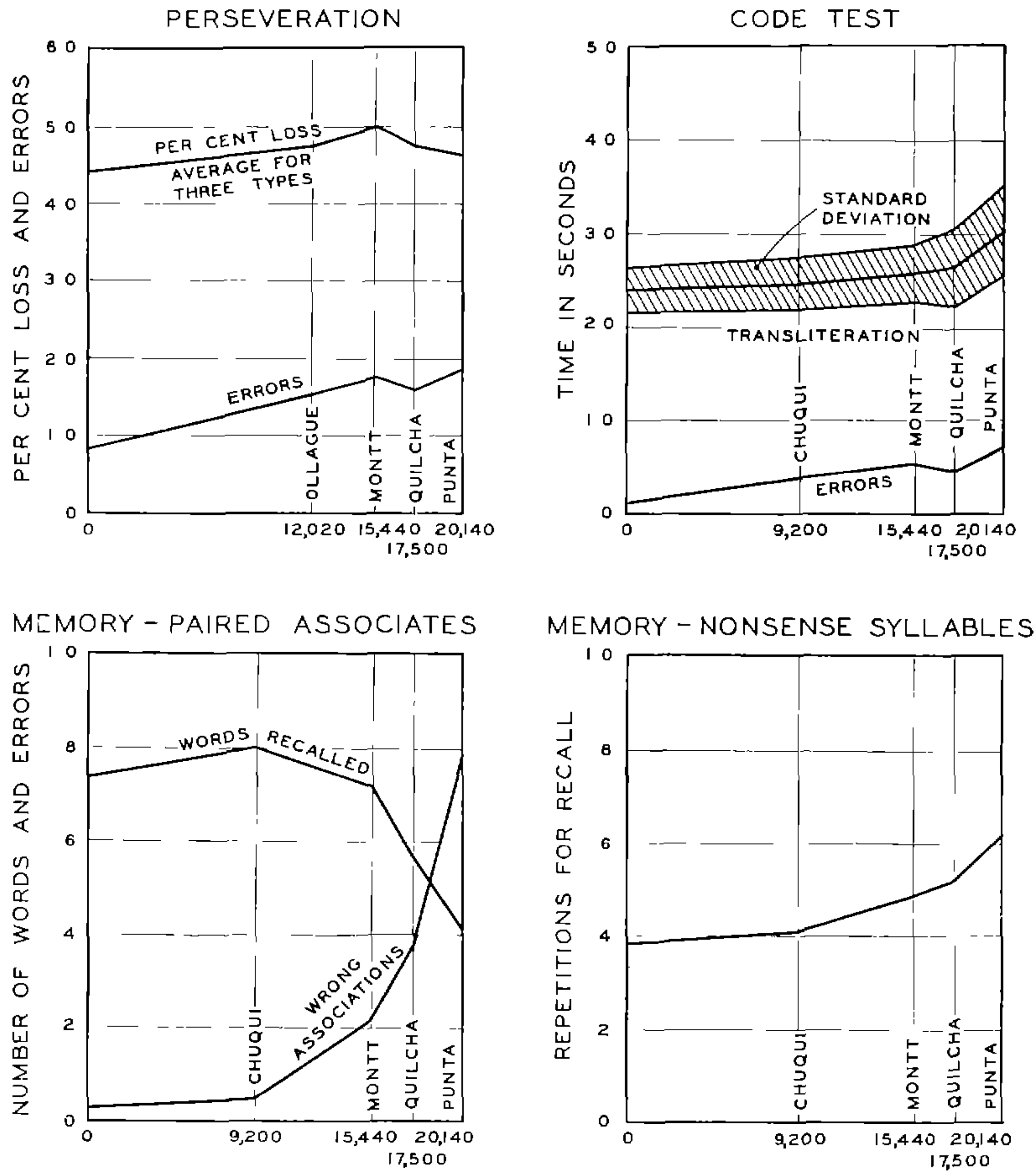


Figure 47 —Effects of altitude on psychological functions (Chilean Expedition, McFarland)

with the response of a large group of subjects classified as to age indicate that there are significant differences in cardiovascular responses One of the most striking differences relates to the fact that there was a tendency for less extreme increases in pulse rate with increasing age That is to say, just as Robinson and Dill observed that the older a subject becomes the less the pulse rate can be elevated in maximum work on the treadmill, so with oxygen deprivation the older the subject becomes the less the pulse rate is increased This indicates that the circulatory mechanisms of adaptation become more stabilized or less flexible with increasing age Cf Figure 36 Although it may be difficult to draw conclusions as to whether this is a good or poor sign of acclimatization, we observed that the older subjects were less susceptible to sudden collapse or fainting than the youngest subjects of 17–22 years of age

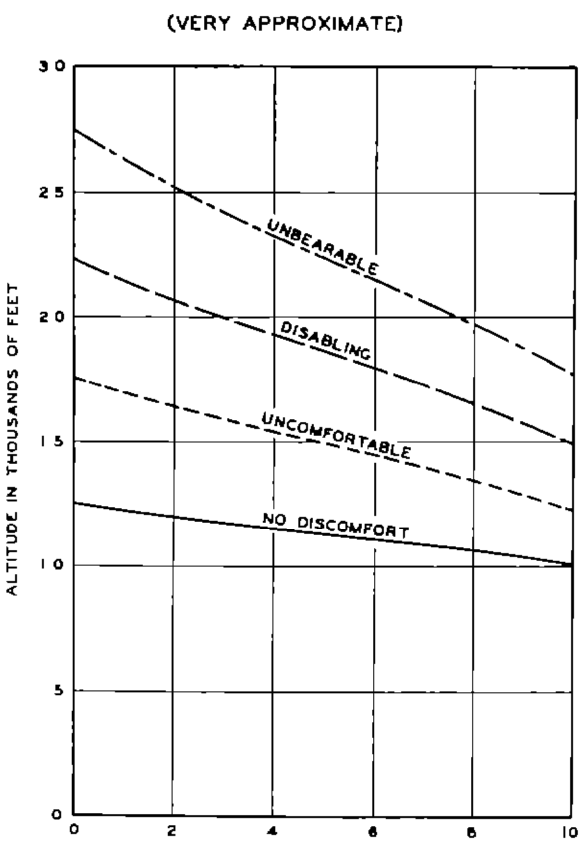


Figure 48 —The effect of altitude shown in relation to length of exposure (McFarland)

General observations on the air lines tend to verify these conclusions in that many subjects over 45 to 50 years of age fly with very few symptoms from the altitude alone

The differences in blood pressure were not so striking as in the pulse rate On the average however, the age group 45 to 70 years showed an average tendency toward an elevated systolic and diastolic blood pressure during the second hour Cf Figure 37 The differences between the various age groups in the partial pressure of alveolar oxygen and carbon dioxide were not significant

The results from the psychological tests indicated that although the older subjects tended to be poorer, on the average, in the control experiments, the relative impairment due to the reduced oxygen pressure was not significant based upon the relative change from a control index=100 Cf Tables 12 to 15, inclusive

An extensive investigation dealing with age as a variable in response to reduced oxygen pressure has recently been carried out in Germany by Schwartz [11] The 237 subjects were studied in a low-pressure chamber The findings, in general, were similar to those from this investigation stated above, namely, that the older subjects showed more stable cardiovascular responses to oxygen deprivation or altitude than the younger ones and in general were less susceptible to collapse or fainting

Physical fitness and psychoneurotic behavior —There are wide variations in ability to tolerate reduced oxygen pressure based upon the physical condition of the person being studied On a number of occasions when the subjects came to the laboratory for the experiments following a night of limited or disturbed sleep or with definite illnesses, such as the grippe, headaches, or indigestion, the responses were perceptibly poorer and more extreme In contrasting the responses of two groups of students, i e, a physically "fit" group and an "unfit" group there were significant differences in both the rapid and slow ascents in the psychological tests, cf Table 22, as well as the physiological

[11] Schwartz W Der Einfluss des Alters auf die Widerstandsfahigkeit gegen Sauerstoffmangel Luftfahrtmed, 1 39–43, 1936

tests, cf Table 21 Practically all of the subjects in poor physical condition collapsed or approached collapse during rapid ascents to 16,000 feet Only two of these subjects, however, collapsed during slow ascents to similar altitudes Only one of the poorer subjects collapsed following a rapid ascent to 12,000 feet

Passengers with marked respiratory or cardiac defects should be discouraged from high-altitude flying because of the possible harmful effects from the reduced oxygen pressure A number of cases have been reported in the literature suggesting that clinical syndromes such as malaria and tubercular disorders may become more accentuated Although it has been suggested that the average cardiac patient *who can walk can also fly*, the altitude should be restricted in patients with decompensated coronary disease so as to avoid any serious effects during or after the flight The average cardiac patient is not apt to collapse during a flight, as witnessed by the fact that so few have actually died on the commercial air transports It is known that under certain degrees of oxygen deprivation coronary vasodilatation occurs, in which case it may well offset, in part, at least, the unfavorable effects of high altitude

The average passenger who becomes too emotionally excited or the one who is suffering from an impairment of the autonomic nervous system is apt to respond to a reduction in oxygen pressure very poorly indeed We observed that psychoneurotic patients from the clinic who were under constant emotional stress and who complained constantly of fatigue and exhaustion were more susceptible to collapse when suddenly placed in simulated altitudes of 18,000 feet compared with control subjects This is in line with a previous study by McFarland and Barach (47) in which they reported that 70

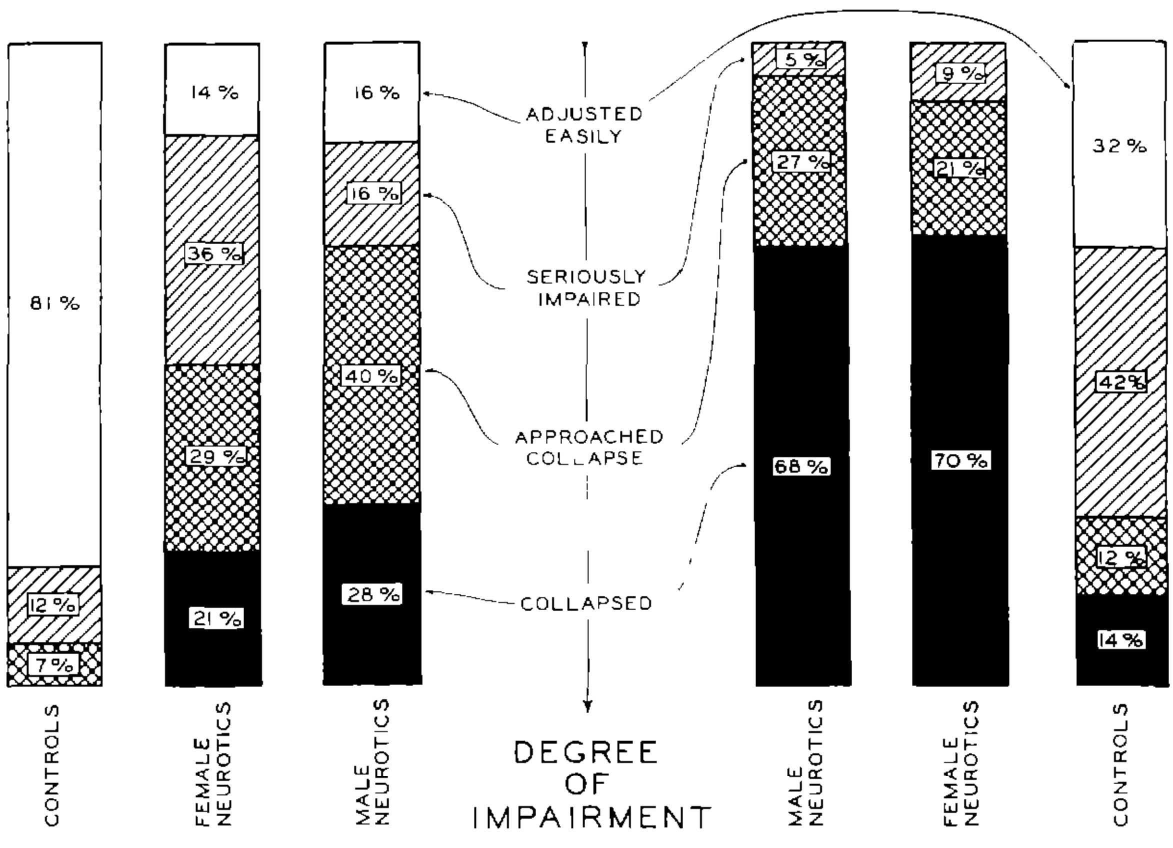


Figure 49—Degree of impairment in psychoneurotic patients under low oxygen (McFarland and Barach)

percent of a group of psychoneurotic patients collapsed when suddenly placed in simulated altitudes of 20,000 feet compared with only 14 percent of the control subjects. Cf. Figure 49. In this investigation the biochemical changes in reduced oxygen pressure were insignificant in the psychoneurotic compared with the control group (cf. Table 29). The neurocirculatory responses were significantly different, however, as manifested in more extreme reactions in pulse and blood pressure. Cf. Tables 26 and 27. This observation is in line with the findings of Schneider (54) who found that pilots who tested below +7 in the Schneider Index were unfit for altitude flying and of McFarland and Huddleson (46) who found that large groups of psychoneurotic patients made a mean score of +7 or below in this index compared with +12 for an unselected group and +14.6 for college athletes. Cf. Figure 50. It is quite possible that those individuals who are under

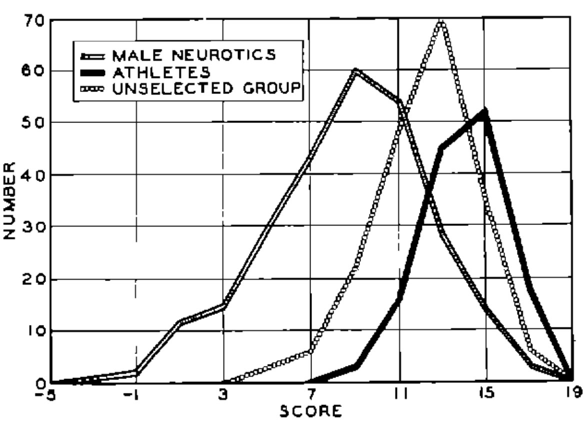


Figure 50.—Schneider Index in psychoneurotic patients (McFarland and Huddleson).

temporary or chronic emotional stress are apt to acclimatize poorly to a reduction in oxygen pressure since the nervous mechanisms involved in adaptation to oxygen lack are reported to be somewhat similar to the ones involved in emotional experiences (sympathetic nervous system). The results of these investigations tend to substantiate the general observations of pilots that passengers who are especially "nervous" or emotionally excited are apt to be affected adversely by high altitude.

ALCOHOL.—Although no special studies have been made in this investigation of the effects of alcohol on the average passenger under reduced oxygen pressure, some evidence is available which indicates that the action of alcohol is greatly accentuated at high altitude. On the Chilean Expedition (reference 7) it was observed that the blood alcohol rose more rapidly and reached a higher level at high altitude (17,500 ft. and 12,000 ft.) than at sea level (cf. Figure 51). If Peters and Van Slyke are cor-

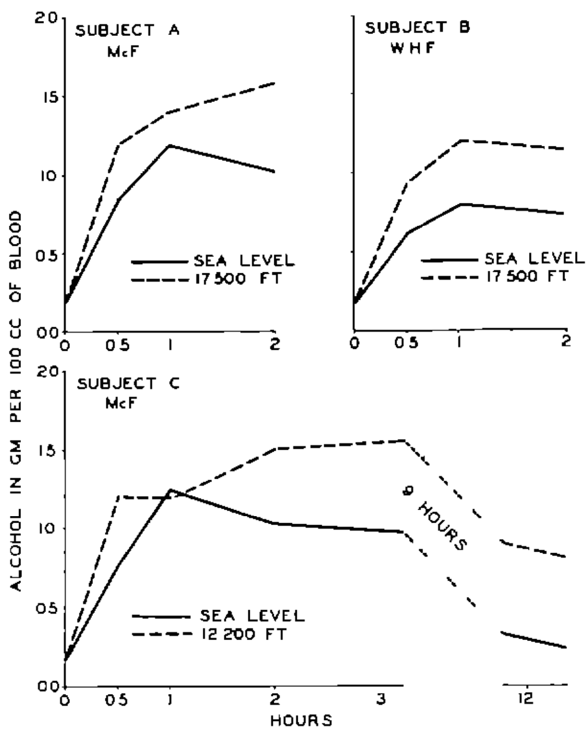


Figure 51.—Rate of oxidation of alcohol at sea level and high altitudes (Chilean Expedition, McFarland and Forbes).

rect in classifying alcohol as a histotoxic anoxia, i. e., an oxygen lack due to the failure of the tissues to be able to utilize the oxygen once it is delivered to them, then at high altitude one would be subject to the effects of both a reduction in oxygen from the atmosphere and from the alcohol as well. This appears to be substantiated from the observations of stewardesses on the commercial air line planes that those who react to altitude most severely as manifested by excessive sleepiness, headaches, or nausea, have indulged in excessive amounts of alcohol previous to the flight The average passenger should be discouraged from the use of alcohol previous to flying The implications are obvious for the pilots who are in control of the airplane

5 *The Role of Carbon Dioxide in Facilitating Acclimatization to High Altitudes* —One of the most important effects of a reduction in oxygen pressure at high altitude is to bring about variations in breathing and an alteration in the delicate balances of the alveolar oxygen and carbon dioxide Numerous experiments, notably those of Y Henderson (30, 31) have shown the beneficial effects of excess amounts of carbon dioxide in clinical syndrones involving respiratory failure In the experiments described above in the low oxygen and low pressure chambers with an excess amount of carbon dioxide (3 0 percent) the beneficial effects were very striking In three different experiments the partial pressure of the alveolar oxygen and the percent saturation of the arterial blood with oxygen were significantly increased Also there was a distinct improvement in the psychological tests (cf Tables 31 to 41) No unpleasant effects were experienced with 3 0 percent carbon dioxide in the inspired air at sea level The results indicate that this amount of carbon dioxide in the inspired air gave rise to an increased pulmonary ventilation and a greater saturation of the arterial blood with oxygen which lowered the altitude by approximately 5 000 feet These findings suggest that an accumulation of 2 to 3 percent of carbon dioxide in the fuselage of an aeroplane might prove to be of practical significance in greatly increasing the pulmonary ventilation and consequently in facilitating acclimatization to high altitude

6 *Interpretation of the Effects of High Altitude on the Human Organism* —The important factor in high altitude which causes the abnormal symptoms is the diminished partial pressure (or concentration) of atmospheric oxygen and the consequent decrease of oxygen in the alveolar air and arterial blood In general the effects of reduced oxygen pressure are approximately the same whether they are brought about in a low oxygen or low pressure chamber or during flights to high altitude in an aeroplane provided the rate of ascent, the length of exposure and the physical characteristics of the individuals are comparable On the average, there is a significant amount of impairment in behavior, both physiologically and psychologically when the partial pressure of oxygen in the alveolar air drops to approximately 50 mm and the saturation of arterial blood is as low as (roughly) 85 percent (approximately 12,000 feet altitude) It should be kept in mind, however, that oxygen lack has profound effects throughout the organism and that there is apparently no single mechanism of acclimatization of outstanding significance

It may be tentatively concluded from these and other studies of the effects of reduced oxygen pressure that the impairment in psychological functions may be attributed to the alterations in both the oxygen and carbon dioxide or more specifically, to the diminished partial pressure of oxygen in the arterial blood being delivered to the nervous tissue This psychological change is probably cellular in origin, rather than due to alterations in circulation, in body temperature, or to the accumulation of unoxidized metabolic products It is known from previous investigations that the alterations in the circulation (16, 28) or in the body temperature (40) must be more extreme than those which occurred in these experiments to bring about an impairment in sensory or mental functions (22) Nor can the loss in efficiency be attributed to the accumulation of lactic acid or other unoxidized metabolic products in the blood (Chilean Expedition, refs 11) The vasomotor reactions known to occur under diminished oxygen pressure produce vasodilatation and increased blood flow to various centers of the brain (23, 39) But the increased blood supply cannot fully compensate for the reduced oxygen supply and as a result the amount of oxygen reaching the cerebral tissue is reduced and the carbon dioxide tension altered (58, 59) The final result is a diminished amount of oxygen being delivered to the brain the cortical elements (or more complex mental functions) being more sensitive to oxygen lack than any other part of the central nervous system (16, 24) The most important abnormal symptoms of high altitude under approximately 30,000 to 35,000 feet, therefore, can be alleviated by the maintenance of a normal partial pressure of oxygen (159 mm Hg) in the inspired air

BIBLIOGRAPHY

1 Anonymous Manual of the Medical Research Laboratory Washington, D C Government Printing Office, 1918

2 Barcroft, J et al Observations upon the effects of high altitudes on the physiological processes of the human body carried out in the Peruvian Andes, chiefly at Cerro de Pasco Philos Trans Roy Soc London, 1923, 211, Ser B, 389 351–480

2A Barcroft, J The Respiratory Function of the Blood Part I Lessons from High Altitudes Cambridge University Press, 1925

3 Barach, A. L, McFarland, R A, and Seitz, C P The effects of oxygen deprivation on complex mental functions Jour Aviation Med, Vol 8, No 4, December 1937

4 Barach, A. L An oxygen chamber simplified in design and operation Anes and Anal, 14 79, 1935

5 Baertschi, W Physiologische-Pathologische Beobachtungen im Hohenflugzeug Schweiz Med Wchnschr, 60 965, 1930

6 Bauer, L H Aviation Medicine Baltimore, Williams & Wilkins, 1926

7 Beyne, J Les troubles provoques dans l'organisme par la navigation aerienne aux grandes altitudes causes mechanisme defence Ann de Physiol 10 331, 1934

8 Bert P La Pression Barometrique Recherches de Physiol Experimentale, Masson, Paris, 1878

9 Bills A G Blocking in mental fatigue and anoxemia compared Jour Exper Psychology 20 437, 1937

10 Birley, J L, Dreyer, G, Flack, M, et al The Medical Problems of Flying Reports I–VII of the Air Medical Investigation Committee His Majesty's Stationery Office, London, 1920

11 Brauer, L, and Strughold H Luftfahrtmedizin Berlin, Springer 1936

12 Campbell, J A The oxygen deficiency theory and experimental tetany Lancet, 1926, 1 72, Jour Physiol, 1925 60 23

12A Cannon, W B The Wisdom of the Body New York, W W Norton & Co, 1932

13 Cannon, W B Stresses and strains of homeostasis Amer Jour Med Sci, 1935, 189 1–14

14 Cannon, W B Bodily Changes in Pain, Hunger, Fear, and Rage 2nd ed, New York, 1929

15 Christensen, E H, and Krogh, A Fliegeruntersuchungen 2 Witt Die Wirkung niedriger O_2 Spannung auf Hohenflieger Skand Archiv fur Physiol, 73 145, 1936

16 Cobb, S, and Freemont-Smith, F The cerebral circulation XVI Changes in the human retinal circulation and in the pressure of the cerebrospinal fluid during inhalation of a mixture of carbon dioxide and oxygen Arch Neurol and Psychiat, 1931, 26 731

17 Dill D B, Christensen, E H and Edwards H T Gas equilibria in the lungs at high altitudes Amer Jour Physiol, 1936, 115 530

18 Douglas, C G, Haldane, J S, Henderson, Y, and Schneider, E C Physiological observations made on Pike's Peak, Colorado, with special reference to adaptation to low barometric pressures Philos Trans Roy Soc Lond, 1913, 203, Ser B, 209 185–318

18A Fisher, R A Statistical Methods for Research Workers Edinburgh, Oliver and Boyd 4th ed, 1932

19 Flack, H The bag method for the investigation of air disabilities of aviators The Medical Problems of Flying Brit Privy Counc, Med Res Counc, 1920, Spec Rep Ser, No 53 14–17

20 Fronius, H Atmung und Stoffwechsal tranierter und untranierter Personen bei Höhenflugen Arbeitsphysiologie, 7 44–61, 1933

21 Fronius H Atmungsphysiologische Studien bei Höhenflugen Schweiz Med Wchnschr, 63 878, 1933

22 Gellhorn, E, and Spiesman I G The influence of hyperpnea and of variations of O_2 and CO_2 tension in the inspired air upon hearing Amer Jour Physiol 1935, 112 519 upon after images, Ibid, 1935, 112 620, upon nystagmus, Ibid, 1935, 112 662 upon visual intensity discrimination, Ibid, 1936, 115 679

23 Gibbs, F A, Gibbs, E L, and Lennox, W G Changes in human cerebral blood flow consequent on alteration in blood gases Amer Jour Physiol, 1935, 111 557

24 Gilden, E F, and Cobb, S The effects of anemia on cerebral cortex of the cat Arch Neurol and Psychiat, 1930, 23 876–903

25 Glaisher, J Travels in the Air London, Bentley, 1871, Rev ed

26 Goralewski, G Zentralnervensystem und Anoxämie Arbeitsphysiologie, 9 94, 1935, Ibid 9 302, 1936

27 Gregg, H W, Lutz B R, and Schneider, E C The changes in the content of hemoglobin and erythrocytes of the blood in man during short exposures to low oxygen Amer Jour Physiol, 50 216, 1919

28 Grollman, A The Cardiac Output of Man in Health and Disease, Charles C Thomas Baltimore, 1932

28A Haldane J S and Priestley, J G Respiration Second ed Yale Univ Press, New Haven 1935
29 Hartman, H Die Wirkung grossen Hohen auf den Organismus vor und nach erfolgter Anpassung Verhandl d Deutsch ges f inn Med 1935 47 48–54
30 Henderson, Y and Haggard, H W The circulation and its measurement Amer Jour Physiol, 1925, 73 1 193–253
31 Henderson, Y, and Radloff, E M The chemical control of breathing, as shown in the acid-base balance of the blood under progressive decrease of oxygen Amer Jour Physiol, 1932, 101, 4 647–661
32 Henderson, Y Seibert, E G Schneider E C Whitney, J L Dunlap K, Wilmer W H Berens, C Lewis E R, and Paton, S Medical studies in aviation I-VII J Amer Med Assoc 1918, 71 17 1382–1400
33 Hill L The limit of high flying when breathing oxygen Proc Roy Soc (b), 1934, 115 298
34 Johnson, H M and Paschal F G Psychological effects of deprivation of oxygen Psychobiology 1920 2 193–236
35 Jongbloed J Über des psychische Verhalten wahrend kurzen Aufenthaltes auf 5000 meter Hohe Klin Wchnschr, 1935, 14 1564 Experimentalle Katatonie durch Unterdruck Arch Neerlandaire de Physiol de l homme et des animaux, 1934 19 538
36 Kaiser W Die Sauerstoffdrosselung in der Atemluft bei Atmospharendruck (Stickstoffnarkose) Med Welt, 1928, 43 1595
37 Kaulen Uber den Einfluss des Fliegens auf das Blutbild bei Menschen Kaninchen und Mausen Deutsch Med Wchnschr, 43 1562 1017
38 Keys A The physiology of life at high altitudes (The International High Altitude Expedition to Chile 1935) Scientific Monthly 1936 43 289
39 Lennox W G and Gibbs E L The blood flow in the brain and the leg of man and the changes induced by alteration of blood gases Jour Clin Invest 1932, 11 1155–1177
40 Loewy A Physiologie des Hohenklimas Springer Berlin, 1932
41 Lowson J P The effect of deprivation of oxygen upon mental processes Brit Jour Psychol 13 417 1923
42 Marshall G S The Physiological Limitations of Flying Aero Rep No 70
43 Mateeff D Gravitationsstoerungen des Kreislaufes bei verminderter Luftdruck Acta Aerophysiologica, 1 73 1935
44 McFarland, R A Psychophysiological studies at high altitude in the Andes Part I The effects of rapid ascents by aeroplane and train Jour Comp Psychol, 23 191, 1937 Part II Sensory and motor responses during acclimatization Ibid 23 227 1937 Part III Mental and psychosomatic responses during acclimatization Ibid, 24 147, 1937 Part IV Sensory and circulatory responses of the Andean resident at 17 500 feet Ibid, 24 189, 1937
45 McFarland R A The psychological effects of oxygen deprivation (anoxemia) on human behavior Arch Psych No 145 Columbia University 1932
46 McFarland R A and Huddleson J H Neurocirculatory reactions in the psychoneuroses studied by the Schneider method Amer Jour Psychiatry 93 567, 1936
47 McFarland R A and Barach A L The response of psychoneurotics to variations in oxygen tension Am Jour Psychol 93 1315, 1937
48 McFarland R A Knehr C A and Berens C The effects of oxygen deprivation on eye movements in reading Jour Exper Psychol, 21 1 1937
49 McFarland R A and Edwards H T The effects of prolonged exposure to altitudes of 8 000 to 12 000 feet during trans Pacific flights Jour Aviation Med Vol 8 No 4 1937
50 Monge C High altitude disease Arch Int Med 1937, 59 32
51 Mosso, A Life of Man on the High Alps (E L Kiesow trans fr 2nd ed, Las Respirazione Periodica) London, Fisher 1898
52 Peters, J P and Van Slyke D D Quantitative Clinical Chemistry Vol I Interpretations Williams & Wilkins Baltimore 1931
53 Schneider E C Respiration at high altitudes Yale Jour Biol and Med, 1932, 4 537
54 Schneider, E C The Physiology of Muscular Exercise, Saunders Phila, 1933
55 Schneider E C A comparison of three types of anoxemia Mil Surg 1924 54 328
56 Schneider E C and Clarke R W Respiratory changes during an aeroplane flight to high altitudes Amer Jour Physiol, 76 354 1926
57 Schnell W Luftfahrtmedizin Berlin, Volkman 1935
58 Schmidt, C F and Pierson J C Intrinsic regulation of blood vessels of medulla oblongata Amer Jour Physiol 1934, 108 241–263
59 Schmidt C F The regulations of circulation in the hypothalamus of the cat Amer Jour Physiol 1934, 110 137
60 Schubert, G Physiologie des menschen in Flugzeug Berlin, Springer, 1935
61 Sillitoe A G A portable reaction time apparatus Brit Jour Psychol 1921 12, 2 147–149
62 Stern, E Ueber den Einfluss kunstlicher Sauerstoffatmung im Hochgebirge Deut Med Wochensch 1926 8 1–10

63 Stern, E Euber die Wirkung künstlicher Sauerstoffatmung im Hochgebirge Klin Wschr, 1925, 4 21

64 Tanaka, K Experimental study on the effects of low barometric pressure and oxygen deprivation upon the efficiency of mental and physical work Rept of the Aero Research Inst, Tokyo Univ No 37, March, 1928

65 U S War Department Air Service Medical Air Service Division of Military Aeronautics, Washington, Government Printing Office 1919

66 Van Ormer E B Retention after intervals of sleep and waking Arch of Psychol, 1932, No 137

67 Wespi, H Ueber psychische insuffiz enzerscheinungen bei vermindertem luftdruck Arbeitsphysiologie, 7 484, 1934

68 Whipple, G M Manual of Mental and Physical Tests Part II Warwick & York, Baltimore, 1915

69 Wright, S Applied Physiology Oxford Univ Press, London, 1931

70 Zuntz, N Löwy, A., Müller, F, u Caspari, W Höhenklima und Bergwanderungen, etc Berlin, Bong 1906

PAPERS FROM THE INTERNATIONAL HIGH ALTITUDE EXPEDITION TO CHILE, 1935

1 The Physiology of Life at High Altitudes Dr Ancel Keyes, The Scientific Monthly, October 1936, Vol XLIII, pp 289–312

2 La Vida en las Grandes Alturas Dr Ancel Keyes, Del Laboratorio Fatigue, Morgan Hall, Universidad de Harvard, Boston, E U A

3 Psycho-Physiological Studies at High Altitude in the Andes

I The Effects of Rapid Ascents by Aeroplane and Train pp 191–225

II Sensory and Motor Responses during Acclimatization pp 227–258

III Mental and Psycho Somatic Responses during Gradual Adaptation pp 147–188

IV Sensory and Circulatory Responses of the Andean Residents at 17 500 Feet pp 189–220

Ross A McFarland, Jour Comp Psychol, Vol 23, No 1 February 1937, Vol 24, No 1, August 1937

7 The Metabolism of Alcohol in Man at High Altitudes R A McFarland and W H Forbes, Human Biology, Vol 8 No 3, September 1936 pp 387–398

8 The Position of the Oxygen Dissociation Curve of Human Blood at High Altitude Ancel Keyes, F G Hall, and E S Guzman Barron, Amer Jour Physiol, Vol 115, No 2, April 1936, pp 292–307

9 Gas Equilibria in the Lungs at High Altitudes D B Dill, E H Christensen, and H T Edwards, Amer Jour Physiol, Vol 115, No 3, May 1936, pp 530–538

10 Morphology and Oxygen Combining Capacity of the Blood J H Talbott, M D Folia Haematologica, 1936, 55, pp 23–36

11 Lactic Acid in Rest and Work at High Altitude H T Edwards, The Amer Jour Physiol, Vol 116, No 2, July 1936, pp 367–375

12 Blood Sugar and Glucose Tolerance at High Altitudes W H Forbes, Amer Jour Physiol, Vol 116, No 2, July 1936, pp 309–316

13 The Effect of Altitude on the Affinity of Hemoglobin for Oxygen F G Hall, Jour Biolog Chem, Vol 115 No 2, September 1936, pp 485–490

14 Comparative Physiology in High Altitudes F G Hall, D B Dill and E S Guzman Barron, Jour of Cellular and Comparative Physiology, Vol 8, No 3, August 1936, pp 301–313

15 Clinical Observations at High Altitude John H Talbott, M D, and D Bruce Dill, Ph D, Amer Jour Medical Sciences, November 1936, No 5 Vol 192, p 626

16 High Altitude Disease Carlos Monge, M D, Arch Internal Med, January, 1937, Vol 59, pp 32–40

17 Acute Mountain Sickness, The Effect of Ammonium Chloride E S Guzman Barron, D B Dill, H T Edwards, and Alberto Hurtado, Jour Clinical Investigation Vol XVI, No 4, July 1937, pp 541–546

18 Sauerstoffaufnahme und respiratorische Funktionen in grossen Hohen E Hohwu Christensen Sonderabdruck aus dem Skandinavischen Archiv fur Physiologie, 1937 Band 76, Heft ½, pp 88–100

19 Der Kreislauf in grossen Hohen E Hohwu Christensen und W H Forbes Sonderabdruck aus dem Skandiavischen Archiv fur Physiologie, 1937 Band 76, Heft ½, pp 75–87