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FEDERAL AVIATION AGENCY
Civil Aeromedical Research Institute
AERONAUTICAL CENTER
OKLAHOMA CITY, OKLAHOMA

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ABSTRACT

The ultimate limitations in flight performance and in future civil air carrier equipment are the limitations imposed by what may be termed "human tolerances." This is particularly applicable to the matter of the supersonic transport. The discussion of man's maximum adaptive capacities for the majority of stresses potentially encountered in atmospheric and transatmospheric flights points to the weakest links in the man-machine complex of air and space transportation. An attempt is made to point out the means by which the human tolerances can be maximally adapted to the advanced technology.

I. INTRODUCTION

In the perpetual struggle for survival on this planet Earth, man has attained a remarkable ability to adapt to a variety of rather adverse environmental conditions. Although increasing technology has succeeded in making life more comfortable and less exposed to nature's perils and, thus, has reduced man's resistance to stress and strain in general, the potential capacity for the full development of adaptive mechanisms fortunately appears preserved in the greater number of individuals. Through training and conditioning many "normal" people can achieve considerable reserves for all sorts of functional demands, and become enabled to excel in conquering new frontiers, to reach the highest mountain summits, to venture into the deep sea, to resist extremely hot or cold environments and to perform amazing physical work feats.

In this new era of technology, in which the human adaptive capacity is eclipsed by the enormous potential of machinery, the full utilization of such superior machinery requires additional devices and techniques to compensate for the evolutionary shortcomings of man. A well known example, in this regard, is the development of modern aviation: from flying "by the seat of his pants," amongst or above some lovely clouds, to the era of flying around the clock under all climatic and weather conditions, the aviator has to be surrounded by more and more equipment. This makes necessary the additional perfection of instrumentation, particularly navigation, communication, and oxygen equipment, and such things as cabin pressurization.

Despite all of the above measures, the technical capabilities of the newest aircraft cannot always be utilized, because the operational demands have to be kept at such a level that the crew and passengers have a sufficient chance of survival in emergency situations. Almost no efforts are made to raise man's psychophysiological limitations to a level where they could match more readily the limitations imposed by their vehicles. This could have been possible where flights did not exceed altitudes of 55 to 60 thousand feet. Now the time has arrived when man begins probing near and outer space.

The supersonic transport, for example, will be a near-space vehicle. Flights beyond the

Earth's atmosphere may at first be comparable to the early attempts of crossing oceans in tiny vulnerable vessels. In these early voyages, many of the sailors preferred to be non-swimmers so that they were spared the agony of fighting certain death in event of a catastrophe. Such a fatalistic attitude, similarly, could be understandable amongst future aeronauts and astronauts, since minor technical failures and incidents affecting the supersonic transport and space craft could lead to inevitable disaster. However, as many strong and powerful sailors have survived the wreckage of their ship and the resulting hopeless situation because of their superior physical condition, so might the survival of some aeronauts and astronauts depend on a maximum of biological reserve and functional capacity.

In the following, then, some aspects of human tolerances for various stress situations are considered from the standpoint of dealing with an "average" individual and/or with an individual who has utilized all potential training and conditioning facilities for achieving his maximum level of adaptive capacity for the stresses anticipated. To cover all of the complex physiological adaptations adequately, a score of contributions by many authorities recognized in their special fields of research is required. In order to keep this report as short as possible, most of its background is based on the experimental facts and experiences gained by the author, both at the U. S. Air Force School of Aviation Medicine, Randolph Field and the Civil Aeromedical Research Institute. References are kept to a minimum, otherwise there would be an abundance of them without, probably, doing justice to the essential publications of many highly qualified investigators.

II. PSYCHO-PHYSIOLOGICAL STRESS

Although much of man's action is governed at will by the central nervous system, most of the interplay between the life sustaining organs is taken out of voluntary control and regulated by the autonomic, or vegetative, nervous system. The central and autonomic nervous systems are so delicately interconnected that merely a visual or auditory perception, or a thought, can spark a vagal or sympathetic response. Such responses may be accompanied by very uncomfortable symptoms. Well known is the pre-show stage fright of experienced actors and speakers, the uneasiness of athletes before competition, and of soldiers before battle. Pounding of the heart, the urge to yawn and overbreathe, unpleasant intestinal upsets, the general feeling of "emptiness" and weakness — these are some of the symptoms preceding dangerous or competitive actions or other activities with a keynote of high suspense. Although such a state of "stage fright" may be experienced as a very unpleasant nuisance, it still is an important phase in the individual's preparation for the imminent event. If geared properly, the predominant influence of the autonomic nervous system provides an adequate functional readiness for any responsive action required. If, on the other hand, the parasympathic and the sympathetic nervous systems are "getting out of phase," then the shifts of blood flow resulting from vasoconstriction in some organs and areas, and vasodilatation in others, are likely to render the individual partially or totally disabled for any quickly required and well-coordinated action.

Human tolerances for mental and psychological stress cannot yet be defined in accurate measures. A given individual might meet similar situations occurring at different times, with different attitudes. Apparently, man's autonomic nervous system is well adaptable, and responds well to training. People who voluntarily burden themselves with tasks of high risks and strenuous work — test pilots, mountain climbers, race drivers, sky and deep sea divers, explorers of the Arctics or jungles — have trained themselves to react, in the event of crisis, almost automatically according to previous experiences or according to reflexes conditioned while imagining and anticipating particular crises.

The best psycho-physiological testing might not enable us to predict precisely an individual's reaction to an unforseen emergency situation. A good advice for the potential "explorer of the unknown" might, therefore, be the following:

A. *Learn to know your limitations for as many physical and mental stresses as possible.*

B. *Learn to tolerate pain, fatigue, hunger and thirst, sleeplessness, heat and cold, the discomfort of high altitude – and frustrations and failures.*

C. *Anticipate all possible emergency situations, and arrive, mentally, at the most proper response.*

D. *Learn to relax completely, confiding into your subconscious the readiness for any sudden demands.*

III. TOLERANCE FOR GRAVITATIONAL FORCES

A. *Acceleration*

The tolerance for acceleration has been determined in human and animal centrifuge studies. The positioning of the body relative to the direction of the increased gravitational forces is found to be critical. In an upright position (headward to footward forces) gravitational shifts of blood may leave the brain cells without adequate blood and oxygen supply, causing "gray-out" or "black-out" at 4-6 gs. If, on the other hand, the accelerating forces are encountered in a right angle to the longitudinal axis of the body, the general distribution of blood is less affected and g-loads up to 10-12 times Earth gravity can be tolerated for 2-3 minutes.(1) Moving or lifting any part of the body against such high centrifugal forces is restricted because of the disproportion between the appropriate muscle groups and the immensely increased weight of the body parts to lift. Even breathing, which involves an active lifting of the chest and/or abdominal wall, becomes an enormously laborious task. Consequently, the decrease in ventilatory activity (hypoventilation), cuts down adequate oxygenation of the blood, first, by not aerating the lung alveoli sufficiently with fresh inspired air and, secondly, by clamping down on the return of venous blood to the heart, thus restricting pulmonary blood flow. Understandably, even in the recumbent or semi-recumbent position, the astronaut's tolerance for acceleration is limited because of the severe oxygen lack developing in the most vitally important organic systems.

B. *Deceleration Tolerance and Effects of Weightlessness*

The tolerance for sudden deceleration may play an important role in atmospheric high speed emergency escape or during a severe landing shock. Truly heroic experimental studies on the biological effects of sudden deceleration have been made by Dr. Stapp on a rocket sled. Accelerated to supersonic speeds, the sled was abruptly stopped. The experiments demonstrated that the human organism can survive, although with severe injuries, a sudden landing shock from a speed of about 100 mph "provided the properly restrained subject is suspended within a capsula in the aft-facing, semi-supine, transverse orientation, and provided the capsula does not fail, crushing in on him."(3)

In deceleration experiments at the Wright Air Development Center, several subjects have tolerated 3 g for one hour, and 4 g for not quite that long.(3) It is questionable, however, if the same individuals would be capable of tolerating a similar "re-entry stress" after they had adjusted to weightlessness in a space flight of extended duration. The evidence accumulated in water immersion experiments suggests that the cardiovascular reflexes necessary for maintaining adequate blood circulation during orthostatic changes, deteriorate considerably when relieved from functioning for any greater length of time.(4) How the complete disorientation of our circulatory system under zero-gravity conditions might affect the cardiodynamics during and after the return to the normal gravitational field can only be told after actual space flights. The more recent events along the space efforts seem to indicate that a space flight of short duration results in much less biological disturbances than a flight of longer duration. There is much speculation about the physiological effects of weightlessness itself. The space physiologist in the orbiting medical laboratory of the future might consider this the number one research problem.

IV. THE PSYCHO-PHYSIOLOGIC PROBLEM OF HYPERVENTILATION

At this point it appears necessary to turn attention to a specific medical problem associated with a variety of stresses, namely to the unconscious increase of breathing activity as response to psychological or environmental disturbances. It was mentioned before that in situations of high suspense, that is under excitement, tension, anxiety and fear, an urge exists to overbreathe. Also, overventilation – or hyperventilation – may occur as response to physical stresses such as milder forms of acceleration, heat or cold exposure, and high altitude. Only in the latter case, at high altitude or under any other condition causing lack of oxygen, hyperventilation has merits of its own. In most other cases it is rather detrimental to man's well-being and performance capacity.

Hyperventilation is understood as an alveolar overventilation, at any given metabolic rate, causing a fall in alveolar carbon dioxide tension, and as a result an increase of the CO_2 tension gradient between tissues, blood and alveoli. Carbon dioxide is then expired from the lungs faster than metabolically produced, and the CO_2 tension in the blood and tissue is lowered—bringing to pass the so-called state of "hypocapnia". Such event is usually accompanied by a series of alarming symtoms such as dizziness, tingling, impairment of vision, spontaneous tightening of muscle groups known as tetany, and even loss of consciousness. Many of these symptoms are identical with those observed in hypoxia, the state of general lack of oxygen. That may come as a surprise but can readily be understood: hypocapnia is known to cause a constriction of the capillary bed in some parts of the organism, especially in the brain. This vasoconstriction may cause a marked decrease in blood flow and oxygen supply and, therefore, the symptoms typical of hypoxia.

A manifestation of more severe hypocapnia are the muscle spasms known as tetany. The diagnosis of "hyperventilation" becomes obvious to the close observer if he notices carpopedal spasms, a development of muscle cramps in the forearms, fingers, and feet. To the remote observer the same diagnosis is justified when audio-communication becomes increasingly difficult: spasms of the facial and neck muscles interfere with the ability to form sounds and words to such extent that the severely hypocapnic individual cannot transmit any verbal messages.

This tetany, occurring in a progressed state of hypocapnia may be a self-defense of the body, to antagonize an excessive loss of carbon dioxide by increased CO_2 production through muscle spasms.

Hypocapnia can be accompanied by a marked reduction or, occasionally, complete loss of performance capacity. The first alarming symptoms might be observed when an individual, by overventilating at better than twice his metabolically required rate, has lowered his alveolar carbon dioxide tension to about 25 mm Hg (from a normal of 40 mm Hg). A three to fourfold increase of breathing above the normally required rate usually lowers the alveolar carbon dioxide tension to about 15 mm Hg and causes, in most cases, a severe reduction in general performance capacity.

The individual susceptibility to hypocapnia varies widely. Some people are observed to faint after a few fast and deep breaths. Others, exposed to a maximum of voluntary overbreathing for relatively long periods of time, never go beyond the stage of minor giddiness. Voluntary repetition of excessive over-ventilation is experimentally found to increase the tolerance for hypocapnia, to almost limitless values. This is of great importance to astronauts, who might be more on edge at times than jet pilots. Inflight studies of the latter have shown that incidents of hyperventilation have accumulated directly in proportion to the greater speed and performance of jet airplanes.(6) Nevertheless, the accident rate did not go up with the higher incidence of hypocapnia. The conclusion is drawn, therefore, that the pilots must have adjusted to this biologically unbalanced situation. Such adaptation to hyperventilation is confirmed in experiments in which several volunteer subjects practiced forced breathing from 30 to 60 minutes daily for a period of two weeks. Although ventilation was finally increased to 5-6 times above the normal rate, and alveolar carbon dioxide tensions as low as 10 to 14 mm Hg were observed, the experimental subjects developed no incapacitation for complex psychomotor tasks.(6) The only explanation for the phenomenon of such adaptability is the unconfirmed hypothesis that the effects of hypocapnia upon local blood circulation, such as vasoconstriction of brain capillaries and vasodilatation elsewhere, might be reduced in intensity after hyperventilation training.

V. HIGH ALTITUDE TOLERANCE

A. *Breathing Normal Air*

The decrease of atmospheric pressure, or more precisely the decrease of the partial pressure of oxygen in the atmospheric air, sets limitations for human operations at high altitude. At about two-thirds of the sea level pressure, equivalent to an altitude of about 12,000 feet, the ability to work is markedly reduced, and a great number of people become temporarily "sick." Fortunately, a long stay at such altitude leads slowly but steadily to full acclimatization, a complex process involving mainly the blood and the blood regenerating organs, the circulatory and the respiratory system, and the kidneys. At the peak of acclimatization, the functioning of the organs has returned to a level almost identical with that at sea level. Adequate altitude acclimatization can provide complete comfort at rest, and satisfactory capacity for strenuous work, up to altitudes of about 18,000 feet, at which the atmospheric pressure is one-half of that at sea level. Beyond this altitude level, however, the physical discomforts during rest, but more so, of course, during any work situation, become increasingly greater until at about one-third of the normal atmosphere, or at an altitude of approximately 28,000 feet, even the optimally acclimatized man has to abstain from greater physical efforts. The amazing fact has to be pointed out, however, that several individuals have been active at a rate of twice or three times their resting metabolic requirements at an altitude of 28,500 feet which would kill a non-acclimated sea-level man within minutes."(7)

B. *Breathing 100 Per Cent Oxygen*

An altitude of 28,000 feet, in space terms, is only an ant hill. More impressive might appear man's adaptability to high altitude if one considers the equivalent altitude he can tolerate when breathing, instead of normal atmospheric air, 100 per cent oxygen through a mask. For example, the mountaineer who, by adequate training and altitude acclimatization, became capable of climbing the highest peaks on Mother Earth without the aid of oxygen may enjoy flying in an unpressurized aircraft at an altitude of 50,000 feet with the aid of breathing 100 per cent oxygen. Hypothesizing on an eventual space event, the well-acclimatized astronaut, after landing on Mars, could leave the protection of his space ship equipped with the same set of oxygen apparatus aviators are using today, and do some first-hand explorations of the new Planet. The atmospheric presssure on Mars approximates, according to estimation, an equivalent altitude of slightly more than 50,000 feet on Earth. All of this has considerable bearing also upon survival in the event of supersonic transport decompression at the 50,000 foot level.

A short elaboration on basic facts of respiratory physiology might help to fully understand the biological limitations of man's conquest of space. Life is a process of continuous energy exchange requiring primarily the presence of oxygen. For adequate transfer of oxygen to the living cell, the driving force of a substantial pressure gradient is essential. The normal pressure of oxygen in the lung alveoli is around 100 mm Hg, while its lowest pressure compatible with survival is around 30 mm Hg for "normal" man, and around 22 mm Hg for individuals optimally acclimatized to high altitude. In the process of inhaling oxygen through a mask, the gas within the mask will be presented under pressure conditions close to those of the surrounding atmosphere. The inhaled gas will then be humidified on its way down the respiratory pathway, and the admixture of water vapor molecules causes a reduction in the partial pressure of inspired oxygen by the displacement of oxygen molecules. At normal body temperature the water vapor tension is 47 mm Hg.

The following examples, depicted in Table I, might help to illustrate the interrelationships of altitudes, gas pressures and biological complications in the act of breathing air or 100 per cent oxygen at very high altitudes.

TABLE I

Altitude Feet	Inspired Gas	Pulm. Ventilation % of "normal"	B	$B\text{-}P_{A\,H_2O}$	$P_{A\,N_2}$	$P_{A\,O_2}$	$P_{A\,CO_2}$
			mm Hg				
500	Air	100	747	700	555	105	40
34,000	O_2	100	192	145	—	105	40
18,000	Air	100	380	333	262	30*	40
44,000	O_2	100	117	70	—	30*	40
44,000	O_2	250	117	70	—	45	25
25,000	Air	300	281	234	185	30*	19
48,000	O_2	300	96	49	—	30*	19

NOTE: B = Barometric pressure in mm Hg; $P_{A\,H_2O}$ = alveolar water vapor tension at body temperature = 47 mm Hg; $P_{A\,N_2}$, etc. = alveolar gas tensions of nitrogen, oxygen, and carbon dioxide, respectively.

*Around the "critical" alveolar oxygen tension of 30 mm Hg, in normal man, loss of consciousness is imminent.

At an altitude of 34,000 feet breathing of 100 per cent oxygen insures, physiologically, the same conditions as breathing normal air at sea level. For 44,000 feet on oxygen the equivalent altitude on ambient air is 18,000 feet. At these altitudes, without adequate regulation of the ventilatory activity, the alveolar oxygen tension attains the "critical" level of 30 mm Hg. At this point the "normal" man loses consciousness. Fortunately, a dangerous lowering of the oxygen tension in the arterial blood is recognized by an appropriate sensing device built into the system of regulating pulmonary ventilation, and breathing is intensified beyond the metabolic needs. With a reflexively or consciously induced overventilation of about 2-3 times the normal rate, the alveolar oxygen tension is raised sufficiently to insure not only survival but even a tolerable amount of work efficiency.

The altitude limits of "normal" individuals are between 18,000 to 25,000 ft, while breathing air, or between 44,000 to 48,000 ft, breathing oxygen, depending entirely on the individual respiratory response to oxygen lack and on the amount of hyperventilation which can be tolerated. In the previous section, dealing with the problems of hyperventilation, the detrimental effects of hypocapnia were discussed. The hypocapic vasoconstriction of brain capillaries could offset the advantages of increased alveolar oxygen tension.

The man acclimatized to high altitude has several factors in his favor for withstanding greater oxygen lack: First, his critical alveolar oxygen tension is markedly lower; secondly, the respiratory center has become more sensitive to oxygen lack and regulates ventilation more adequately according to needs; thirdly, the continuous hyperventilation associated with extended exposure to high altitude has reduced or abolished the deteriorating effects of severe hypocapnia.

The interrelationship of the alveolar gas tensions at altitudes where a sufficiently effective level of mental and physical working capacity is maintained, and at other altitudes where the critical blackout point is close at hand, is shown in Table II. "Normal" individuals, never having been exposed to high altitude for any considerable length of time, are compared with men optimally acclimatized to altitudes. The figures presented are based on actual high altitude experimentation breathing 100 per cent oxygen:

TABLE II

	Altitude Feet	B	$P_{A\,O_2}$	$P_{A\,CO_2}$	Pulm. Vent. (normal = 100%)
		mm Hg			
Normal man:					
"Tolerable" Hypoxia	45,500	108	36	25	250%
"Critical" Hypoxia	48,000	96	30	19	300%
Acclimatized man:					
"Tolerable" Hypoxia	50,000	87	27	13	400%
"Critical" Hypoxia	52,000	79	24	8	550%

B = barometric pressure = the sum of the alveolar oxygen, carbon dioxide and water vapor tensions.

In these experiments, the ascent to high altitude was accomplished gradually over a period of several minutes. The adaptability to a very rapid onset of severe hypoxia would have been less favorable.

C. *Breathing Oxygen Under Pressure*

The altitude ceiling can be further raised by providing oxygen under a pressure exceeding the surrounding atmospheric pressure. This technique has never been applied to greater extent because of certain drawbacks. The normal breathing mechanics are geared in such a way that inspiration is an overwhelming active muscular process while expiration, usually, is almost entirely passive. The negative pressure occurring during the inspiratory enlargement of the chest cavity promotes the return of venous blood into the thorax and, thus, into the heart. During the expiratory phase the intrapulmonic pressure does not increase substantially enough to restrict venous return markedly. In positive pressure breathing, the inspiration is usually passive and the respiratory gas is forced into the lungs. Venous return, therefore, is not assisted by the development of a negative intrapulmonic pressure during the inspiratory phase and is furthermore inhibited by the considerable pressure within the thorax during expiration. Positive inspiratory pressure can result in an overstretching of the diaphragmatic muscle and of lung tissue—if it is not properly counterbalanced by a continuous tension of the abdominal and the other muscle groups usually contributing to forced expiration. The continuous contraction of these muscles is, of course, progressively fatiguing, especially at the higher mask pressures.

For a while the physiological disadvantages of pressure breathing were overemphasized. In fact, complete circulatory failure was predicted at positive mask pressures of about 30 mm Hg.(8) Logically, in further work on providing protection of the aviator in emergency situations at very high altitude, ways and means were sought and found to counteract the positive oxygen pressure in the helmet or mask by providing a sufficiently high pressure on the body as a whole.

Certainly, pressure breathing without the assistance and/or protection of a pressurized garment is limited and means hard physical work of usually neglected muscle groups. Like any other strenuous work, it can be kept up for a limited length of time only. However, the circulatory embarrassment, caused by the mentioned restriction of venous blood return, can sufficiently be taken care of by applying a breathing technique different from the one described: (9) instead of letting the thorax passively expand under the positive gas pressure — which gives a brief moment of subjective relaxation for the straining expiratory muscles! —short but active inspirations are made after forced expirations. The difference between the two techniques can be felt immediately: at a more critical positive mask pressure, about 30 mm Hg, an experimental subject becomes dizzy and "scared" while using the passive inflation technique; two or three breaths employing the forced inhalation technique let him regain full consciousness and a feeling of security.

Although the application of pressure breathing is apparently complicated by the high degree of hypoxia present at extreme altitudes, and consequently by the excessive hyperventilation required for maximum altitude tolerance, experimental evidence has been presented that pressure breathing can raise the altitude ceiling considerably without harmful risks to the individual. (10) Table III demonstrates to what extent "normal" and altitude acclimatized men are able to increase their ceiling when inhaling oxygen under pressures found to be feasible and tolerable. Any lowering of the atmospheric pressure below the "tolerable" or "critical" levels, shown in Table II, has to be compensated for by an equivalent increase of oxygen pressure in the mask. Knowing a man's altitude tolerance and his tolerance for pressure breathing, his "safe" and/or "critical" ceiling can readily be predicted.

TABLE III

	A_1	B_1	P_M	B_2	A_2
	Feet	mm Hg			Feet
Normal man:					
"Tolerable" Hypoxia	45,500	108	+20	88	50,000
"Critical" Hypoxia	48,000	96	+25	71	54,000
Acclimatized Man:					
"Tolerable" Hypoxia	50,000	87	+27	60	58,000
"Critical" Hypoxia	52,000	79	+35	44	64,000

NOTE: A_1 and B_1 are altitudes and pressures traced from Table II; P_M = oxygen pressure in the mask; B_2 and A_2 are minimum barometric pressure and maximum altitude attainable.

The "critical" values, as shown, are of theoretical interest only. During pressure breathing full consciousness has to be preserved in order to prevent damaging lung expansion. Approaching unconsciousness would disable man from adequately controlling the required coordination of delicate activities.

The figures in Table III, obtained through actual experimentation with several subjects, indicate what benefits regarding altitude tolerance are to be expected from altitude acclimatization and proper training.

D. Pressure Suit

A sudden exposure to altitudes in excess of 50,000 feet requires the protection afforded by a pressure suit. The time of useful consciousness could be counted in seconds when less than 100 per cent oxygen was inhaled for a greater length of time before the incident. Even an immediately initiated nose-down of an airplane might, under such conditions, not prevent several crew members and passengers from going through a temporary state of unconsciousness. Breathing of oxygen prior to an incidental loss of cabin pressure has a protective effect due to the almost complete elimination of gaseous nitrogen which otherwise would compete with oxygen, carbon dioxide and water vapor in filling the alveolar spaces. After prior breathing of 100 per cent oxygen, in a case of sudden decompression, an automatic delivery of oxygen under pressure, compensated for by an automatic inflation of the pressure suit, should permit a continuation of the mission – if all crew members were likewise protected and had followed strictly the oxygen discipline.

There are practically no altitude limitations for a man fitted with – and properly indoctrinated in the use of – a pressure or space suit. Under space conditions, an altitude acclimatized man might be sufficiently effective in a space suit pressurized to 115 mm Hg or to slightly more than 2 p.s.i., while the "normal" individual would require an oxygen pressure of at least 3 p.s.i.

VI. DYSBARISM OR DECOMPRESSION SICKNESS

A serious threat to high altitude flying is the development of severe symptoms of decompression sickness in the incident of cabin pressure loss. A similar threat would exist for the astronaut in such a case – if pressure and gas composition were kept at a normal atmospheric level in the space capsule. Even the space suit would not prevent the occurrence of bends, chokes or other symptoms, occasionally taking a very serious development. The individual susceptibility to decompression sickness may depend on age, body fat, general physical condition, and on neuro-muscular tensions. Breathing 100 per cent oxygen for several hours, or living for 1-2 days under atmospheric conditions equivalent to 14,000 feet, afford complete protection against bends, etc.,(11) at barometric pressures as low as 50-60 mm Hg, and therefore, of course, also against the occurrence of decompression sickness when exposed to space conditions but protected by the space suit. Those considerations are important for providing the adequate gas composition and pressure conditions in the living quarters of any extraterrestrial vehicle.

VII. TOLERANCE FOR HYPERCAPNIA

In space operations, the loss of oxygen pressure or the accumulation of carbon dioxide in the sealed crew compartments could be one or the other main cause of an environmental emergency situation. While considerable protection against severe hypoxia can be obtained by altitude acclimatization, the latter appears, on first sight, not to be compatible with sufficient tolerance for higher levels of carbon dioxide in the inspired air. The reason for that is the increased sensitivity of the respiratory center to carbon dioxide, after biochemical adjustments to chronic hyperventilation had been made during altitude exposure. In work experiments done at sea level before and immediately after acclimatization to about 14,000 feet, pulmonary ventilation for the identical work intensity was 125 and 160 l/min, respectively.(12) In these experiments metabolic carbon dioxide production, and therefore the quantitative CO_2 stimulus for respiration, were identical.

In another experiment, carbon dioxide was allowed to accumulate, during light physical exercise, by rebreathing an oxygen enriched gas mixture. The results are shown in Table IV.

TABLE IV

% CO_2 in air	Ventilation during work of 400 Kgm/min liters/min (BTPS) Pre-Acclim.	Post-Acclim.
.05	27	31
5.0	56	62
7.5	77	95
10.0	124	158

These experiments demonstrated certain things. *First*: subjective symptoms such as dizziness, far-away feeling, headache and dyspnea are very poor indicators of the true physiological limitations for hypercapnia. *Second*: the cardiocirculatory system, although definitely responding to CO_2 accumulation, is not stressed to full capacity, as Table V indicates.

TABLE V

Inspired gas	Ventilation 1/min	Blood Pressure mm Hg	Pulse Rate F/min
Air	27	145/80	96
10% CO_2 in air	124	200/100	130

Third: the best criterion for the tolerance of carbon dioxide was the attainment of the maximum breathing capacity, whereby the latter essentially equalled that observed during maximum physical efforts. Experiments with the same individuals before and after altitude acclimatization demonstrated that the critical CO_2 concentration in the inspired air reached 10 per cent in both experimental phases. The ventilatory response in the control experiments was 124 1/min (BTPS) while it was 158 1/min after acclimatization. The difference between these two values of maximum breathing capacity must be explained as an effect of adaptation to high altitude. There, because the demands on pulmonary ventilation are considerably increased, the greater breathing efforts, especially during physical work, develop greater strength and endurance of the respiratory muscles. Hence, a greater maximum breathing capacity is achieved during altitude exposure. *Fourth*: despite the increase in sensitivity of the respiratory center to CO_2 the tolerance for the altitude acclimatized man remained, practically, unaltered because he was able to respond with increased pulmonary ventilation, as discussed previously.

VIII. TOLERANCE FOR TEMPERATURE EXTREMES

During many of the imaginable space operations of the future, the adaptability of man to extreme variations in temperatures might become of considerable importance. The human tolerance limits for environmental temperatures depend on the critical body temperatures at which the functioning of the living cell rapidly deteriorates. At the lower end, cold narcosis sets in when the body temperature decreases to 32-30°C; at the higher end, core temperatures of about 44°C are incompatible with life. Within the relatively narrow zone of plus or minus 5-7°C the body has to regulate its temperature in response to potential environmental temperature changes from such lows as about −35°C to such highs as 50°C, that is within a zone from around −70 to +13°C on both sides of the body's 37°C. It follows that man should be more adaptable to cold than to heat. Nevertheless, more people apparently die from cold than from heat exposure. That, apparently, is directly related with the capacity for physical work because in absence of any efficient external protection the body protects itself against loss of temperature by heat generation through muscular activity. Increased energy metabolism depends, however, on adequate energy sources within the body or on sufficient energy supply. In the cold, shivering can increase the metabolic rate up to four times above basal conditions.(18) The greater part of our population can only tolerate a threefold increase for a few hours before becoming extremely fatigued. Thus, without adequate shelter, the poorly conditioned individual might not be able to survive a long period of exposure to temperatures around the freezing point. The physically well-conditioned individual, however, can tolerate extremely cold situations for days and weeks by maintaining just the proper amount of activity. About four-fifths of the energy expenditure in rest and in physical work are "wasted" on elevating or preserving body temperature.

In contrast, heat exposure demands a reduction or cessation of physical efforts. The only physiological defense against overheating is the evaporative cooling of the body surface, combined with a highly increased blood flow through this area. Adequate evaporative cooling is dependent, of course, on the humidity of the surrounding air, and on sufficient body fluids. Functionally, the main load is carried by the circulatory system and the functional limitations of the latter, more or less, determine heat tolerance.

In extraterrestrial operations excessive temperature stresses will invariably be combined with other stresses such as hypoxia, hypo- or hypercapnia, high humidity, or high g-forces. These and other variables—clothing, radiation, air movement, and possibly a change of physical condition during long space operations—makes it impossible to predict accurately, in terms of centigrades, the tolerable temperature extremes. The biological space laboratories of the future will certainly help in adding more data to the already extensive literature on the effects of environmental temperatures under complex stress situations.

IX. TOLERANCE FOR PHYSICAL WORK

Why this last section on physical work capacity? Is not the future astronaut and space explorer bound to be very inactive because of narrow living quarters and long periods of weightlessness? Why should one be interested how many foot pounds of work a candidate for outer-space could do in a given time?

The answer is simple: The capacity for physical work is the best criterion of physical fitness. Everyone appears to agree that excellent physical fitness is one of the main prerequisites for the man who is going to face all sorts of unprecedented mental, psychological and physical stress situations and hardships. However, the agreement stops right there since everyone has his own ideas about "fitness." What are the differences between poor, good, excellent or superior physical fitness, or physical condition? Does a clean bill of health, given to a number of individuals, mean that all these individuals will have the same potential capacity to withstand successfully the same life endangering emergency situations? The question here is not about differences in skill or training or mental attitudes or experiences! The only concern here is: What, in healthy individuals, does constitute differences in their physical condition, enabling some to survive more or less unharmed while others are perishing, some sooner, some later? Looking at physical fitness from such a point of view might help to reach a better agreement on its basic principles.

A. *Functional Limitations*

The functional limitations of work capacity can be assessed adequately in relatively complex but short tests, involving gradually increasing work intensities which will evoke, finally, maximum cardiovascular and respiratory responses. The best criterion for the adaptive capacity of the circulatory system should be the maximum cardiac output. Unfortunately, direct measurement of blood flow cannot be made in human experimentation, and even the indirect measurements require elaborate techniques. As an apparently poor substitute, pulse rate and blood pressure can be measured routinely Most recent investigations have indicated that this substitution does not offer so poor results after all. In fact, it allowed for a very close estimation of the relative changes in cardiac output.

Like any other pump, the heart can change the flow of blood by changes of the stroke, of the frequency of strokes, and by a combination of both. In recent years much emphasis was turned toward the concept that the heart responds to increased demands almost entirely with a speed-up of the rate of contractions, keeping the stroke volume nearly unchanged. The basis for this concept was mainly gained from experiments with animals and/or with hospitalized male patients. Children and many women might react similarly. However, for the high energy expenditures seen in many men at work and sports, this concept is unacceptable. Since heart rate can only increase to approximately three times its resting rate under maximum physical demands, the blood flow under such conditions would be completely inadequate without augmentation of the stroke volume. In fact, past and most recent experimentations with "normal" men in good physical condition have left no doubt that the heart does use both alternatives simultaneously during strenuous work. Stroke volumes have been found to increase up to almost twice the resting value. Thus, maximum cardiac output of 5 to 6 times resting blood flow rates were measured. The definite limitations observed consisted either in the attainment of a maximum pulse rate without any further increase in stroke volume or a marked diminution of stroke volume at heart rates in excess of 180-190 beats per minute.

It was interesting to observe that the routinely measured changes in blood pressure correlated well with the changes of stroke volume during physical work. In the light of these findings, the telemetered, or otherwise recorded physiological data of pulse rate and blood pressure may allow for a close estimation of the pilots' and astronauts' functional responses in flight, and how far the reserve capacity of their circulatory systems might become engaged in coping with stress situations.

Functional work capacity is also limited by the strength and endurance of the respiratory muscles to force the rate and depths of inspiration and expiration, in other words, by the maximum breathing capacity under high demands. Usually, the well-conditioned man can increase his resting ventilation approximately 20 times, the poorly conditioned man only 10 to 15 times. In addition, the pulmonary ventilation is more efficient in the former than in the latter when compared on the basis of actual energy exchange.

Both the circulatory as well as the respiratory limitations, can be expressed in one single criterion: the maximum oxygen intake. Whenever at further increasing work intensities oxygen consumption reaches a constant level, the functional adaptability is outdone. For the physiologist or physician familiar with the evaluation of physical fitness, any individual's maximum oxygen intake, expressed in ml/min/kg, means a certain place on the functional fitness scale.

B. Metabolic Limitations

The metabolic limitations of work capacity can be assessed during strenuous but submaximal work of longer duration. The body's glycogen stores are usually running low after close to two hours of strenuous physical activity. Fat depots are also utilized for energy supply as long as carbohydrates are available in sufficient amounts. An exhaustion of carbohydrates terminates the capacity for further physical work. Individuals in poor physical condition may have carbohydrate reserves of only 100-150 grams while exceedingly well-trained men may have stored about 400 g of glycogen in the liver and muscles.(14) The latter cannot only work at a much higher rate and for a longer period than the former because of the higher glycogen stores but also because of the ability, probably "learned" in training, to utilize to a greater extent the body fat as an energy source. This greater fat mobilization was ascertained by higher blood lipid levels during strenuous exercise of long duration.

C. Environmental Effects on Work Capacity

Tolerance for physical work is a variable depending upon periods of inactivity or increased activity, upon fatigue or latent infectious disease and, certainly not to the least, upon environmental effects. In the following, three particular environmental stresses are selected because of their specific demands on one or the other physiological function.

1. HEAT

The assumption is made that a man, engaged in a regular conditioning program, is accustomed to run at moderate temperatures of around 22°C (=72°F) a course of 5 miles in 40 minutes. With a body weight of 75 kg (167 lbs), the intensity of work involved in running at that speed demands an oxygen intake of nearly 3400 ml /min and, accordingly, a cardiac output of approximately 30 l/min. These values are assumed to represent this individual's tolerance limits for maximum steady state work.

Supposedly, within a day or two, the outside temperature climbs to 35°C (=95°F). Our experimental subject, maintaining his running routine, feels well on the first mile, starts pushing to keep the same speed on the second mile, reduces the speed considerably on the third because "he just does not have it today," becomes so "fatigued" on the fourth mile that he slows down to walking and trotting, and can make the last mile only by alternatingly pausing and walking.

What had happened? Soon after the first 8-10 minutes of strenuous work the body's mechanisms for regulating temperature are intensified, and extremely so at unusually high environmental temperatures. As a result, a much greater part of the total blood flow is shunted to the body's surface area and thus withdrawn from the blood flow necessary to maintain the aerobic energy exchange in the musculature. Since cardiac output already was maximal, no further compensatory adaptations were possible. Muscular activity had to be reduced to a level which constituted a compromise between blood flow required for cooling of the body and that available for continuation of work. Because of their encroachment on circulatory limitations, the effects of high temperatures have caused reductions of work capacity by 25 per cent and more.

Of course, there will be immediate criticism from someone saying that the astronaut will not be engaged in really strenuous work. In view of such criticism, it might be worthwhile to look at the problem from the reversed angle — how much circulatory reserve capacity is left during a severe heat stress? Heat tolerance tests are usually terminated when the experimental subject's pulse rate has risen to a frequency of 160 beats per minute, almost to three times the resting value. Blood pressure, at that point, is usually increased also. Cardiac output, therefore, must have been increased close to three times the resting value of about 7 liters per minute, that is to 21 l/min. Most "normal" men of "average" physical condition have only a potential capacity for 25 l/min total blood flow. Therefore, there are not many reserves left at extremely high temperatures and the slightest additional stress, requiring further circulatory adaptations, might complicate the situation beyond possible physiological solutions.

2. ALTITUDE

Work capacity in acute altitude exposure is reduced because of the higher requirements imposed upon circulation and pulmonary ventilation by the lack of oxygen in the atmosphere. In men who have become acclimatized to altitude, the circulatory response for any given work load may have returned to more normal because of advantageous changes in the blood. Then only the maximum breathing capacity sets the limitations for work. Although, as was discussed in the section on altitude stress, maximum breathing capacity increases during "active" altitude exposure considerably, from about 125 l/min to approximately 180 l/min (BTPS), there it reaches a definite limit. Table VI may help to explain what reduction in work capacity must be expected at various altitudes.

Because of an almost 50 per cent rise of maximum breathing capacity (M.B.C.) after three weeks of acclimatization to the altitude of 10,000 feet the work capacity there practically equalled that previously attained at sea level. After 6-8 weeks spent at the 14,000 foot level no further increase in M.B.C. was observed and work capacity was definitely reduced 13 per cent.

In the Himalayan Mountains man has climbed up to altitudes between 28,000 and 29,000 feet without the use of oxygen. In these events a metabolic rate of 3-4 times basal metabolic conditions must have been maintained for a few hours, requiring, theoretically, a pulmonary ventilation of approximately 90 l/min. Actually, the breathing efforts must have been much greater. Since the acclimatization processes reach a plateau approximately at 23,000 feet, any ascent beyond that altitude level requires for a maximally acclimatized individual similar adaptive mechanisms as an acute ascent of a normal man from sea level to medium altitudes of 10,000 to 14,000, or more feet. One should expect, therefore, that these mountaineers, climbing upward on Mt. Everest at an altitude of 28,600 feet, must have been working closely at their circulatory and respiratory limitations.

TABLE VI

V_{O_2}	ml/min	250	1000	1500	2000	2500	3000	3500	4000
Vent. (STPD)	1/min	5	20	30	41	52	68	83	100
Alt. in ft.		Ventilation		(BTPS)		liters/Min.			
500		6.5	25	37	51	64	84	103	123
10,000		9.5	36	54	74	94	123	149	181
14,000		11	43	65	89	112	147	178	
18,000		13	52	78	107	135	177		
24,000		18	70	105	143	182			
28,500		22	89	134	183				

V_{O_2} = oxygen intake, under basal metabolic conditions to maximum aerobic work capacity

Vent. (STPD) – pulmonary ventilation at 0°C, 760 mm Hg, dry

Vent. (BTPS) – "true" pulm. ventilation, saturated with H_2O at body temp. at the environmental barometric pressure.

An astronaut, having an identical level of altitude acclimatization, should be able to perform work of 2-3 times his basal metabolic rate under environmental conditions equivalent to 50,000 feet – when breathing oxygen.

C. COLD

The functional capacity for work – as actual experimentation has shown – is not directly affected by severe cold. Metabolic work capacity, however – that is the maximum energy expenditure accumulated during steady work – is considerably reduced when severe cold shivering competes – either preceding or in rest pauses – with the work task. In a wet-cold environment the exhaustion of metabolic reserves can be fatal. The following example may illustrate the close relationship between general physical condition and tolerance for combined work-cold stress.

Three experienced mountaineers – one of them a mountain guide in top physical condition, the other two, after a long "inactive" winter "out of shape" – climbed a not difficult mountain in the early pre-summer season. Temperatures were close to the freezing point, the ground toward the peak was covered with ice and snow, and frequent rain or sleet showers soaked the clothing. After a two-hour ascent, a rest period was taken by the two weaker members of the party, while the third climbed to the peak and returned within one hour. During the rest period the former two ate a little but were severely harassed by icy winds and snow flurries. Immediately after the party had rejoined, descent was begun but it became very slow because of vehemently progressing "fatigue" of the two less trained climbers who shivered violently and became weaker and weaker. Helping one of them down a more difficult spot, the leader, suddenly, held a dead body in his arms.

Concentrating on getting the third man safely down, the guide used all the tricks of the trade to force this man's actions. At the beginning of an easy trail, leading downhill within a one-half hour, at a fast pace, to an inhabited shelter cabin, the man gave up – utterly exhausted. By now unable to carry his companion to safety, the guide bedded him down in a place well-protected against the weather, covered him with all the extra clothes available and with a survival nylon sack – and hurried down to alert a rescue team. Two hours later such a team returned – but found the man lifeless.

A great many of such incidents happen annually also in the plains where severe blizzards might trap scores of people. The knowledge we gain from such tragedies is: The poorly conditioned man can fight cold for only a relatively short time until his energy stores (carbohydrates) are exhausted. In considering many of the spaceman's future missions requiring activities outside his sheltering "home" – whatever it will be – the limited work capacity of man under extreme cold situations should be kept in mind!

The best chances for survival under critical stress, whatever stress complication might be encountered, are assured by superb physical conditions. Exactly at the time this was written, the first American astronaut completed successfully an orbital flight. This was just the beginning of an endless series of further probing into deeper and deeper space – with more and more psycho-physiological demands. The future will tell us to what extent human tolerance limits for complex stresses can be stretched by the very specialized training needed for mastering the extraterrestrial universe.

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