SCIENCE

VOL. 95 FRIDAY, FEBRUARY 27, 1942 No. 2461

SCIENCE: A Weekly Journal devoted to the Advancement of Science, edited by J. MCKEEN CATTELL and published every Friday by

THE SCIENCE PRESS

Lancaster, Pa. Garrison, N. Y.

Annual Subscription, $6.00 Single Copies, 15 Cts.

SCIENCE is the official organ of the American Association for the Advancement of Science. Information regarding membership in the Association may be secured from the office of the permanent secretary in the Smithsonian Institution Building, Washington, D. C.

PHYSIOLOGY AND HIGH ALTITUDE FLYING: WITH PARTICULAR REFERENCE TO AIR EMBOLISM AND THE EFFECTS OF ACCELERATION[1]

By Dr. J. F. FULTON

LABORATORY OF PHYSIOLOGY, YALE UNIVERSITY SCHOOL OF MEDICINE

I. INTRODUCTION

"YE who listen with credulity to the whispers of fancy, and pursue with eagerness the phantoms of hope; who expect that age will perform the promises of youth, and that the deficiencies of the present day will be supplied by the morrow; attend to the history of Rasselas, prince by Abissinia.

"Rasselas was the fourth son of the mighty emperour, in whose dominions the Father of waters begins his course; whose bounty pours down the streams of plenty, and scatters over half the world the harvests of Egypt.

"According to the custom which has descended from age to age among the monarchs of the torrid zone, Rasselas was confined in a private palace, with the other sons and daughters of Abissinian royalty, till the order of succession should call him to the throne."

AND the account goes on to say that the palace of Rasselas was in a spacious Abyssinian valley into which came artists and men of science to advance the

[1] Sigma Xi Lecture delivered before the Yale Chapter in Sage Hall, Yale University, Wednesday, October 15, 1941, and The Duke University Medical Defense Symposium, October 16, 1941.

culture of its happy Utopian population. It so happened one year that a famous artist and engineer came to the valley to settle and the young prince made frequent visits to his house. One day the engineer told Rasselas:

"I have been long of opinion, that, instead of the tardy conveyance of ships and chariots, man might use the swifter migration of wings; that the fields of air are open to knowledge, and that only ignorance and idleness need crawl upon the ground (1, p. 35).... He that can swim needs not despair to fly; to swim is to fly in a grosser fluid, and to fly is to swim in a subtler. We are only to proportion our power of resistance to the different density of the matter through which we are to pass. You will be necessarily up borne by the air, if you can renew any impulse upon it, faster than the air can recede from the pressure (1, p. 36)....

"The labour of rising from the ground," said the artist, "will be great, as we see it in the heavier domestick fowls; but, as we mount higher, the earth's attraction, and the body's gravity, will be gradually diminished, till we shall arrive at a region where the man will float in the air without any tendency to fall: no care will then be necessary, but to move forwards, which the gentlest impulse will effect" (1, p. 37–38).

At this juncture Rasselas thought his engineer had gone astray and interjected,

"All this . . . is much to be desired, but I am afraid that no man will be able to breathe in these regions of speculation and tranquility. I have been told, that respiration is difficult upon lofty mountains, yet from these precipices, though so high as to produce great tenuity of the air, it is very easy to fall: therefore I suspect, that from any height, where life can be supported, there may be danger of too quick descent" (1, p. 39).

Rasselas, although unconvinced, was interested and urged the engineer to proceed. This he did under one condition, namely, that Rasselas would divulge to no one the secret of making wings.

"Why," said Rasselas, "should you envy others so great an advantage? All skill ought to be exerted for universal good; every man has owed much to others, and ought to repay the kindness that he has received."

"If men were all virtuous," returned the artist, "I should with great alacrity teach them all to fly. But what would be the security of the good, if the bad could at pleasure invade them from the sky? Against an army sailing through the clouds neither walls, nor mountains, nor seas, could afford any security. A flight of northern savages might hover in the wind, and light at once with irresistible violence upon the capital of a fruitful region that was rolling under them. Even this valley, the retreat of princes, the abode of happiness"—this Abissinia—"might be violated by the sudden descent of some of the naked nations that swarm on the coast of the southern sea" (1, p. 41).

And so Rasselas promised secrecy. The wings were made and the wings were tried, but, like Icarus, the inventor fell into the sea, for he lacked the motive power to flap his wings; and Rasselas rescued his engineer from a watery grave.

Thus, ladies and gentlemen, did Samuel Johnson in 1759 depict the problems of aviation medicine and their relation to warfare. Rasselas was something of a physiologist by temperament, his friend was an inventive engineer, but the engineer was also a realist, for he insisted that certain things can not for the moment be told to the world lest it jeopardize the "security of the good."

If the history of aviation were to be written one would come quickly to appreciate Dr. Johnson's astonishing prescience in characterizing so vividly the developments of modern aeronautics. The modern aeronautical engineer has placed primary emphasis upon design, upon the attainment of speed and quick manoeuverability; in some modern combat planes virtually everything has been sacrificed to gain these two objectives—everything sacrificed including the pilot. It is no secret, for example, that until very recently some of the new bombers designed to fly at 35,000 feet were so cold inside at that altitude as to make it quite impossible for a crew to function effectively for more than a few minutes. I will return to this in a moment.

The second development in modern combat flying has arisen from recognition of the need for protecting the pilot, and at long last aviation engineers are getting together with flight surgeons—and even with physiologists—recognizing that the physical limitations of the pilot are quite as important as the physical characteristics of the machine, and that both must be considered in designing and operating combat aircraft. I propose to deal with three phases of the problem, all essentially physiological, affecting pilot performance at high altitudes, (i) temperature, (ii) aero-embolism and (iii) effects of high acceleration.

II. Temperature

Under standard atmospheric conditions the temperature at 38,000 feet is 55° below zero Fahrenheit; above that stratospheric level the temperature falls but little. The pilot, or the gunner in the open turret, exposed to such a temperature for 8 hours with a wind velocity of 20 m.p.h. is worthless as a gunner; occasionally indeed he has turned out to be a cake of ice.

There have been many studies in war and in peace time of the influence of cold on human performance. In a word, exposure to intense cold for a sufficient duration to cause perceptible lowering of the rectal temperature makes motor performance slow and inaccurate, and cerebral activity, as indicated by the ability to solve simple problems or to follow simple directions by radio, is gravely impaired. As with nearly all problems involving stress, some individuals are much more affected than others.

The designing engineers have given us planes that will fly to 35,000 and even 40,000 feet, but at first they largely forgot the pilot and the crew, believing that inconveniences from extremes of temperature could be taken care of by clothes from Quartermaster Corps. In single-motored fighter planes, there is little trouble from cold, even in the high altitude ranges, since the pilot sits behind the engine and the cockpit receives direct warmth from it; but in all larger twin-motored or four-motored planes, especially the long-range bombers, the bomb bay is generally open to the outside air and the heating arrangements, especially in the American-made planes, were not only inadequate, but in some of the better known the heating facilities are virtually useless, heaters having been put in the top instead of the bottom of the fusilage. Enormous quantities of heat are available from the exhaust of the long-range bombers, and with little alteration in basic design the exhaust could be made to heat any strategic point in the plane, including the gunner's position. The gunner is more exposed to cold than any other member of the air crew, for in most planes his station in the blister receives the full blast of outside air from the horizontal machine-gun aperture, and in a long mission, the gunner may be at his position for eight hours or more at an altitude of 20,000 feet, at which level the outside temperature would be 25° below zero.

Numerous proposals have been made to combat low temperatures, *e.g.,* electrically heated suits, boots and gloves, and there have been many designs of other types of clothing. Most acute, however, is the need for an oxygen mask and an oxygen line of supply that does not freeze up during prolonged exposure to low temperatures. The Army and Navy have recently released for manufacturers their criteria for oxygen supply systems in which they insist that the oxygen mask and accessory supply valves must not freeze up in one hour with temperature −40° Centigrade in the face of a wind velocity of 10 m.p.h. at an altitude of 37,500 feet. Every mask commercially available at the present time freezes up solid after about 10 minutes of such punishment. Those of you who have recently seen the popular film "Dive Bomber" will have had vividly portrayed the consequences of a frozen system of oxygen supply.

And there are also many vicious circles in connection with cold and high altitude. If very heavy clothing is worn, the crew must do more work in moving about and hence require more oxygen. If the oxygen supply clogs or freezes at 35,000 feet, especially that of a crew member moving heavy bombs, he falls unconscious within 15 seconds or less and the duties of other crew members are generally of such a nature as to prevent their giving prompt assistance. I can not tell you in detail how the problem of cold is being met here or in England, but one can say this, that the flight surgeon is still forced to employ many awkward expedients—all of them I hope temporary—until the heating engineers have solved their phase of the problem, which includes heating, as well as ventilation and also watching for carbon monoxide and other toxic gases.

III. Aero-Embolism

Some of the faster interceptor planes may gain altitude at the surprising rate of a mile a minute; this brings them, if that rate of ascent is maintained, from sea level to 35,000 feet in roughly 7 minutes. Actually, the rate of ascent is inevitably slower in the rarefied air, but it is stated in the newspapers that some of our new fighters have attained altitudes of 36,000 and 37,000 feet within 10 minutes of the time they took off. The pressure of air at 34,000 feet is a quarter of that at sea-level atmosphere—190 mm Hg instead of 760 mm. An aviator arising to 34,000 feet thus subjects himself to the same relative decompression as that experienced by a diver ascending from 100 feet of water—which is equivalent to 4 atmospheres—to the surface level. If a diver ascends too rapidly, nitrogen bubbles tend to form in the tissues and blood stream, and in the same way aviators who subject themselves to rapid decompression are likely to experience the symptoms of bubble formation in their tissues. To divers and to caisson workers, the painful syndrome has long been known as "bends" because the excruciating character of the pains causes those affected to "double up."

The tendency of bubbles to form in the blood under conditions of decompression was first observed by Robert Boyle in the course of those celebrated experiments in which he weighed the air, determined the reciprocal relationship between volume and pressure, and compared combustion with respiration (1662). Boyle observed that when freshly drawn blood was placed in a decompression chamber bubbles were evolved on the surface of the blood as air was being sucked out of the chamber. He asked himself whether these bubbles did not represent the fraction of the air normally taken up when blood passes through the lungs. If this were true, he argued, bubbles should appear in the blood vessels of animals subjected to rapid decompression. Although Boyle's premise was not wholly correct he was led through this reasoning to make one of the most important observations in the history of our subject. Small bubbles do, in fact, appear in the circulating blood of animals subjected to decompression and this is how Boyle described it in a short note in the *Philosophical Transactions* for September 12, 1670 (2).

Note, that the two foregoing Experiments were made with an Eye cast upon the inquiry, that I thought might be made; Whether, and how far the destructive operation of our Engin upon the included Animal, might be imputed to this, that upon the withdrawing of the Air, besides the removal of what the Airs presence contributes to life, the little Bubbles generated upon the absence of the Air in th Bloud, juyces, and soft parts of the Body, may by their Vast number, and their conspiring distention, variously streighten in some places, and stretch in others, the Vessels, especially the smaller ones, that convey the Bloud and Nourishment; and so by choaking up some passages, and vitiating the figure of others, disturbe or hinder the due circulation of the Bloud? Not to mention the pains that such distensions may cause in some Nerves, and membranous parts, which by irritating some of them into Convulsions may hasten the death of Animals, and destroy them sooner by occasion of that irritation, than they would be destroyed by the bare absence or loss of what the Air is necessary to supply them with, and to shew how this production of Bubbles reaches even to very minute parts of the Body, I shall add on this occasion (hoping that I have not prevented my self on any other,) what may seem somewhat strange, what I once observed in a *Viper*, furiously tortured in our Exhausted Receiver, namely that it had manifestly a conspicuous Bubble moving to and fro in the waterish humour of one of its Eyes [p. 2044].

Within the past year, our public press has made a great to-do about the dangers of aero-embolism in aviation, and unfortunately the popularity given to the subject has made the average military flier unduly apprehensive about the dangers of "bends." Owing to the developments of the last year, most of which are about to be described in an important paper by Lieutenant Commander A. R. Behnke in the next number of the *Military Surgeon*, "bends" would seem no longer to be a serious problem in military aviation. I would like to state this categorically, and if the press is disposed to cite anything from this paper I hope it will stress this point. The new developments may be briefly outlined as follows:

1. Denitrogenation (*a*) *with oxygen.* It has long been suspected that "bends" arise primarily from nitrogen bubbles rather than from oxygen, carbon dioxide or the rarer gases, since nitrogen comprises 80 per cent. of normal air and is rather slow to pass through cell membranes. Once a nitrogen bubble appears, therefore, it is not rapidly absorbed. By breathing pure oxygen for a prolonged period, all the nitrogen of the body, or virtually all of it, can be disposed of. Dr. Behnke (3) has found that when the body is completely denitrogenated, previously susceptible subjects fail, after exposure of several hours to altitudes of 40,000 feet, to develop "bends." Unfortunately the curve of nitrogen elimination shown in Fig. 1 indicates that pure oxygen must be breathed

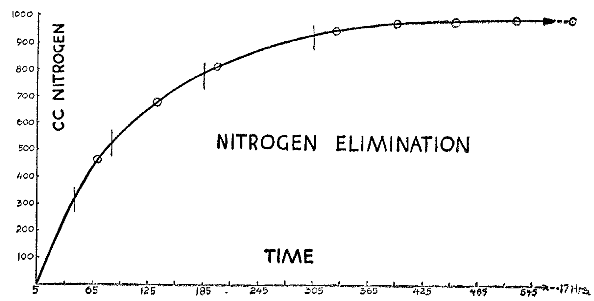

Fig. 1

for at least five hours before 95 per cent. of the body's nitrogen is eliminated. Obviously, therefore, preoxygenation is not a feasible way of preventing "bends," especially for fighter pilots who could not be expected to stay in an atmosphere of pure oxygen for five hours prior to each ascent. The same is true of bomber crews. However, an hour of breathing pure oxygen, as, for example, if the pilot puts on his oxygen mask immediately he enters his plane, will diminish "bends" susceptibility, but will not prevent its ultimate appearance if the exposure to high altitude continues for a long period. In a susceptible subject studied by Commander Behnke severe "bends" developed between 25,000 and 28,000 feet without preoxygenation. With 45 minutes preoxygenation "bends" did not develop until 30,000 feet; with 90 minutes preoxygenation the ceiling was raised to 34,000 feet; with 3 hours to 37,000 feet and after 5 hours preoxygenation the "bends"-susceptible subject withstood 40,000 feet for 2 full hours without experiencing symptoms.

(*b*) *Helium.* Oxygen for prolonged administration is hazardous because of its toxicity. Nitrogen can be removed as effectively from the body of a helium-oxygen mixture as with pure oxygen. Since helium is only one third as soluble in fat as is nitrogen, the quantity of gas available for bubble formation, especially in the bone marrow, which comprises as much as 90 per cent. fat, is greatly reduced. If a human being were saturated with helium, instead of nitrogen, it would require only 90 minutes of oxygen inhalation to eliminate dissolved helium in contrast to the 5-hour period for nitrogen elimination. Commander Behnke believes it would be practicable to have bomber pilots in a ready room filled with an atmosphere of oxygen and helium prior to flight. So far, however, this proposal has not had service trial.

Preselection for high altitude service. The susceptibility to "bends" varies enormously in different individuals, and little is known as yet of the basis for the differing susceptibilities. The younger age groups are less susceptible than the older, and any one having an injury to a joint is prone to develop "bends" at the site of injury. Pilots in the age group of 18 to 24 can often withstand prolonged exposures to altitudes as high as 40,000 feet without developing the symptoms. Behnke and others have recently stressed this point, and it has now become possible on the basis of decompression chamber tests to single out for the high altitude squadrons those pilots who can stand, say, 35,000 feet for 4 hours without developing untoward symptoms. At least 50 per cent. of the young adult population fall into this category, and it is probable that with training the percentage will be even larger. Hence, if pilots are selected through preliminary decompression chamber tests as fit for high altitude operations, "bends" ceases to be a serious military problem.

All the preventive measures elucidated by Commander Behnke and others, even for those who appear to be unsusceptible to "bends," such as taking oxygen from the ground up, ascending slowly and indulging in the limited amount of exercise possible in the cockpit of a plane, are also recommended for observance.

It is possible that certain drugs may diminish "bends"-susceptibility, but as yet there is no panacea for protecting a susceptible subject except for a full 5 hours of preoxygenation.

IV. EFFECTS OF ACCELERATION

An aircraft flying along the curve of any circle, whether in pulling out of a dive, a tight turn or a diving spiral will have acting upon it from the center of the circle a centrifugal acceleration which varies directly as the square of the linear velocity and inversely as the radius of the circle. The actual weight attained by a body during acceleration is the product of the mass and the acceleration expressed in terms of the normal attraction of gravity, *i.e.*, 1 *g*. At a centrifugal acceleration of 7 times the force of gravity (7 *g*), a pilot weighing 180 pounds normally would have a weight, so long as the 7 *g* is sustained, of 1,260 pounds. Every tissue in the body takes part in this increase in weight and as the current RAF *Manual* puts it "at 6.9 *g* the blood becomes as heavy as molten iron." During such acceleration the weight of the hydrostatic column of blood is too great for the heart to cope with on the arterial side and venous blood fails to be returned to the heart from regions of the body below the cardiac level. Hence there tends to be a pooling of blood in the abdomen and lower extremities and failure of the cerebral circulation. The effect of diminished circulation to the retina of the eye manifests itself in graying, and, finally, in ultimate failure of vision—giving the phenomenon of "blackout." When vision goes, consciousness is likely to fail shortly thereafter.

There is a time factor in acceleration as important physiologically as the absolute magnitude of the centrifugal force itself. The average young adult can withstand sitting in the upright position 5 *g* for 4.5 seconds. He might also stand 7 *g* for 2 seconds, but no normal adult can withstand 7 *g* for 7 seconds without complete loss of consciousness. This means that neurons of the brain are so intimately dependent upon their supply of oxygen that when this is withdrawn by centrifugalizing the blood away from the head consciousness lapses, usually within 5 seconds.

The capacity to withstand acceleration varies in different individuals, and in the same individual at different times. Test pilots have found that an alcoholic spree of an evening considerably diminishes their tolerance for positive acceleration the next day. Relative anoxia, such as may occur in high altitudes when the oxygen supply is inadequate, likewise diminishes resistance to acceleration, and it is likely that the level of the blood sugar is similarly important. In recent German literature various expedients have been recommended to assist the pilot to withstand positive acceleration. These may be enumerated briefly.

1. Full stomach. In the recently published diary, "I was a Nazi Flier," there is a diverting chapter on aviation medical research in Germany in which it is stated that all resistance on the part of pilots to being experimented upon was overcome when it became known that the "doctors" had recommended that the pilots of Stuka dive bombers should have a large beefsteak before going off on a mission! From other sources (*e.g.*, Ruff and Strughold, 1939, 4) it is clear that the German flight surgeons insist that an empty stomach diminishes tolerance to high acceleration. When the stomach is full the visceral blood vessels are also distended so that more blood can not readily enter them—so runs the German explanation. Blood chemistry, no doubt, also plays a part in determining resistance to *g*.

2. Carbon dioxide. Use of 5 or 6 per cent. carbon dioxide, which through increasing the cerebral circulation is said by the Germans to increase resistance to acceleration by 1 to 2 *g*. (Ruff and Strughold). This is doubted by other authorities.

3. Vasoconstrictor drugs. Any pharmaceutical agent which increases the "tone" of the capillary wall improves one's *g* ceiling. Pituitrin, adrenalin and adrenal cortical hormones have all been mentioned in this connection, but precise data concerning these are not available.

4. *Pneumatic belts.* Mechanical constriction of the abdomen as well as of the lower extremities has also been proposed in both the German and English literature to minimize the rush of blood from the head to the visceral bed and the lower extremities. Of these mechanical devices, pneumatic belts and pneumatic trousers have been most under discussion. The Germans state that a pneumatic belt may increase g tolerance by 1 to 1.5, but no one of the present belligerent countries has permitted publication of detailed reports concerning the actual effectiveness of this equipment.

5. *Water suits.* The Germans have also reported on a "water suit" designed for the prevention of blacking out, and while they claim it notably improves resistance to positive acceleration they state that it is unsatisfactory for other reasons. To quote Grow and Armstrong (1941, pp. 276–277):

> The water suit is a closely fitted water-proof garment which is worn next to the skin. What little space is left in the suit after it is put on is filled with water or other suitable fluid. This causes the flier to ''float'' in the suit, and during accelerations the water presses on the body equally in all directions. As a consequence the normal effects of acceleration are replaced by a uniform compression of the body which, it is estimated, could be tolerated without difficulty up to 15 gs or more.

6. *Posture.* In a recent paper by Ruff (1940) in *Medizinische Klinik* the problem of posture in relation to acceleration was discussed. The Germans, it appears, favor a crouching posture with flexion of the legs against the abdomen as one particularly suited for protection of the pilot against acceleration. This would bring the hydrostatic column of blood in the leg veins nearer to the heart level. If the pilot lies supine or prone at the end of a dive-bombing manoeuvre, he is also less subject to negative accelerations, but in these postures he is unable to see out or to manoeuvre his plane without special redesigning of the cockpit and the cockpit controls.

It should be noted that all factors tending to improve the body's resistance to positive acceleration are those which tend to keep blood in the head. From this it may be concluded that the phenomenon of blacking-out and loss of consciousness which may occur within 5 seconds of the beginning of the acceleration is probably due solely to acute anoxia, and can not be attributed to any direct effect of acceleration *per se* upon the cortical neurons.

V. Conclusion

Many other phases of aviation medicine might be discussed, but since there are certain topics that can not be gone into fully at the present time—having in mind Rasselas's "Security of the good"—I have omitted mention of night vision, instrument lighting, the oxygen mask, the adrenals and Drs. Nims and Clarke's studies of pH in anoxia, until some later time when restrictions are less imperative than at present. I hope, however, that I have been able to indicate some of the more important developments as well as the intensely fascinating character of the problems encountered.

I believe that the successful solution of several problems in aviation medicine will determine in large measure the outcome of the present war.

REFERENCES

1. Johnson, Samuel. *The Prince of Abissinia.* 2d ed. London, 1759. 2 vol.
2. Boyle, R. New pneumatical observations concerning respiration. *Philos. Trans.*, 1670, *5:* 2011–2031; 2035–2056.
3. Behnke, A. R. High atmospheric pressure. *Ann. intern. Med.*, 1940, *13:* 2217–2228.
4. Ruff, S., and Strughold, H. *Grundriss der Luftfahrtmedizin.* Leipzig, J. A. Barth, 1939. 191 pp.
5. Grow, M. C., and Armstrong, H. G. *Fit to fly.* New York: D. Appleton-Century Co., 1941. 387 pp.
6. Ruff, S. Ueber den Kreislaufkollaps bei grossen Beschleunigungen im Flugzeug. *Med. Klin.*, 1940, *36:* 749–756.

THE PROBLEM OF THE EXPANDING UNIVERSE[1]

By Dr. EDWIN HUBBLE
MOUNT WILSON OBSERVATORY

Mathematics deals with possible worlds, with the infinite number of logically consistent systems. Observers explore the one particular world we inhabit. Between stands the theorist. He studies possible worlds but only those which are consistent with the information furnished by the observer. In other words, theory attempts to segregate the minimum number of possible worlds which must contain the world we inhabit. Then the observer, with new factual information, reduces the list still further. And so it goes, observation and theory advancing together toward the common goal of science, the structure and behavior of the physical universe in which we live.

The relation is evident in the history of cosmology. The study at first was pure speculation. But slowly, as the exploration of space moved outward, a body of

[1] Abstract of annual Sigma Xi address before the American Association for the Advancement of Science, Dallas, Texas, December 30, 1941.