SPACE MEDICINE

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PREFACE

Manned space flight has become a reality, but information about the effects of such adventure on both mind and body is still severely limited.

Space medicine is a science devoted to obtaining this information. It is related to ecology, the study of the relation between living organisms and their environment, and is thus a part of environmental medicine. As such, it is interested in both the physical factors of the space environment and the physiological effects such factors have on man. Space medicine is also preventive medicine. As such it aims at the ultimate goal of all medical practice—the recognition and prevention of abnormal response patterns to stress before they become rigidly fixed into classically recognizable disease patterns manifested by permanent structural and functional disturbances.

Space medicine offers a new vantage point for observing the effects of environmental stress on all forms of life. The procedure of selecting, evaluating, training, protecting, and equipping an astronaut for space flight will provide much insight and knowledge about the response of the human body to many types of stress. Much new instrumentation is being developed in this endeavor as well. Breaching the space frontier will supply important new information in biology, medicine, and medical electronics, which may also apply to man in his terrestrial environment. This data should be made readily available to all interested in human welfare.

This ideal has not been realized. In spite of an urgent need, information about space medicine is not readily available. Space medicine has developed rapidly, almost explosively, during the last few years. Since it obtains its information from many sources, this information is often widely scattered. Not only the practicing physician, but even the research investigator in the field often has difficulty finding well-organized information on space medicine. Some can be found in the classical textbooks of physiology and aviation medicine, but most is widely dispersed in both the open literature and in numerous unclassified government reports. Treatises and symposia on space medicine or space science usually consist of collections of papers by various authors, each of whom is interested in his own particular field. This profusion of detailed, specialized, and at times esoteric information only serves to confuse any but the initiated investigator.

This book is a basic textbook relating known and well-established physical and physiological facts of manned space flight. It is not a progress report but concentrates on basic knowledge. It emphasizes the experimental conditions, often only simulating those encountered in space, under which this knowledge was obtained. While further experience in actual space flight may extend and amplify this knowledge, the basic principles discussed here will remain valid.

In the following pages the various factors of space medicine are discussed in three broad categories: The reactions of man to the physical factors in the space environment; the dynamic factors of space flight; and the psychophysiological factors of the space-cabin environment. In each chapter, the physical environment of space, the space cabin, or space flight is described first, and then the biological effects of these factors are analyzed. Those mainly interested in the design and engineering aspects of space flight may wish to skim most of the biological material. For them, the last paragraph under "clinical syndrome" will sufficiently delineate man's tolerance for the factors of the space environment. Finally, not only the therapeutic drugs or physiological methods of adaptation which may increase man's tolerance for the stresses encountered in space and space flight, but also the engineering and design criteria which man's limited tolerance imposes on the design of the spaceship cabin are discussed under "prevention."

This book is a basic introduction to space medicine. It offers continuity of thought and progressive development of the subject, and focuses on the physiopathologic importance of space ecology. It is written for the aerospace engineer whose limited time does not permit him to collect and synthesize the diversified material now available, and for the busy physician who would like to satisfy his interest in an active, rapidly expanding, timely field. It attempts to give a comprehensible account of the major physiological and physical factors which underlie and direct the development of our efforts to launch man into the Space Age. The inclusion of a pertinent, basic bibliography at the end of each chapter will serve as a valuable reference guide for those who would like to explore a particular phase more intensively.

U.T.S.

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INTRODUCTION

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MAN'S ENTRY INTO SPACE

THE CONCEPT OF SPACE FLIGHT

Man's yearning to explore the distant stars and planets is probably as old as human thought. Soaring birds and twinkling stars in the sky beckoned him to leave his terrestrial confines in both waking fancy and in dreams. The idea of human flight can be found in the Hindu Vedas of 2000 B.C., in the Sanskrit Bhagavata, in early Persian and Egyptian literature, and in Inca and Mayan writings, as well as in the more familiar Greek mythology. However, none of the means of achieving propulsion proposed in this literature—for example, harnessing birds, attaching artificial wings to the arms or shoulders of a man, and using lode stones or even rockets—may be considered a serious scientific proposal.

It was Leonardo da Vinci (1452–1519) who first experimented seriously with designs and models of aircraft (3), and a Russian, Konstantin Ziolkowski * (1898), who first gave serious technical thought to space flight. In 1903, Ziolkowski wrote *Investigation of World Space by Reactive Instruments*, in which he suggested the use of the rocket as a means of obtaining the propulsion necessary for space travel. Almost a quarter of a century later these ideas were expanded by the American rocket pioneer, Robert H. Goddard, who published *A Method of Reaching Extreme Altitudes* in 1920, and by the Hungarian-born German, Hermann Oberth, who published his *Die Rackete zu den Planetenräumen* (The Rocket into Interplanetary Space) in 1923 (1,3). These studies

* Also transliterated Tsiolkovski.

moved space flight from the realm of science fiction to that of technology.

A vehicle for space flight must be able to function in an environment which imposes special requirements on its design. This environment is difficult to define, however. Physically, space is that region where the earth's atmosphere ends. This material limit of space is somewhere between 1000 and 2000 km (600 and 1200 miles).* At this altitude, one cubic centimeter of air contains less than one million particles (23), a vacuum harder than any obtainable in terrestrial laboratories. However, recent data obtained during the International Geophysical Year suggest that the earth's atmosphere may merge gradually with the sun's corona, so that there is no clean-cut region where the earth's atmosphere ceases. Hence, a physical definition of space is elusive. Since space medicine is mainly concerned with the physiological effects of the space environment, a physiological definition of space is more useful for its purposes. In 1951, Strughold, Haber, *et al.* suggested that the atmosphere ceases and space begins at different altitudes for different physiological functions. They named this altitude the region of *Space Equivalence*, or the *Functional Border of Space* for the function under consideration (10,23,25).

One of these atmospheric functions that may be considered is the supply of oxygen for metabolic combustion. All living terrestrial organisms need oxygen in some form to supply their physiological energy needs. An unacclimatized man, living at sea level, experiences hypoxia, or lack of oxygen in the atmosphere, at an altitude of about 3 km (10,000 ft). At such altitudes he may suffer shortness of breath, dizziness, inefficiency, headaches, poor judgment, and inability to concentrate. Unless this condition is corrected, unconsciousness may result. While the arterial blood is still 90 per cent saturated with oxygen at 3 km, it loses its oxygen content rapidly at higher altitudes; at 5.4 km (18,000 ft), it is only 70 per cent saturated. These factors are fully discussed in Chapter 2; here, it suffices to state that man reaches the first functional border of space, the space-equivalent region for hypoxia, at 3 km. For flights above this altitude, supplemental oxygen must be supplied.

The space-equivalent region for anoxia, or total absence of oxygen, occurs at 15 km (50,000 ft). Although the atmosphere still contains 21 per cent oxygen, the atmospheric pressure is equal to that of the water vapor and carbon dioxide in the lungs. Hence, no air from the atmosphere can enter the alveoli, or air sacs, of the lungs. Were this atmosphere to contain 100 per cent oxygen, the oxygen would still be unavailable to the body through respiration because of the ambient pressure at this

* For definition of units, list of abbreviations, and conversions from English to metric systems, see the appendix.

altitude. Thus, oxygen must be supplied to a pilot under pressure. Since breathing against increased pressure through an oxygen mask produces rapid fatigue of the muscles of respiration, it is advisable to supply this pressure to the entire body surface, either by placing the man in a pressure suit or in a pressurized cabin.

At 24 km (80,000 ft) the oxygen content of the atmosphere becomes insufficient for any conventional vehicle, such as a jet plane, which relies on atmospheric oxygen for the combustion of its fuel. Above this altitude, a vehicle must carry its own oxygen supply or use some fuel, such as atomic power, which does not require oxidation.

The atmosphere provides not only oxygen for combustion to both man and machine, but also a certain amount of pressure. At sea level, this pressure is 14.7 pounds per square inch (psi) or enough to raise a column of mercury to a height of 760 mm in a vacuum tube (760 mm Hg). Oxygen, essential to human metabolism, is carried in the blood mainly in chemical combination with hemoglobin. Hence, the oxygen content of the blood is not directly related to atmospheric pressure. However, other metabolically inert gases that are carried mainly in solution in the blood and body fluids obey Henry's law, so that the amount of such gases dissolved in the body fluids and blood is directly proportional to the atmospheric pressure and depends on the partial pressure of the gas in the atmosphere above the solution. Nitrogen, which constitutes 78 per cent of the atmosphere, is the major inert gas thus dissolved in the body. A decrease in atmospheric pressure will allow some of the dissolved nitrogen to come out of solution. If the pressure change is large, and the rate of change rapid, severe pain and other serious consequences may occur (this effect is fully discussed in Chapter 2). This condition has been known for a long time as the "bends" by caisson workers and deep sea divers—men who work under pressures greater than the atmosphere's. It is named dysbarism (3) when it occurs during exposure to pressures lower than that of the atmosphere, such as in high-altitude flight. Dysbarism may occur at altitudes above 6.5 km (22,000 ft), unless the necessary precautions are taken.

At 20 km (60,000 ft to 67,000 ft) atmospheric pressure is so low that water will boil at normal body temperature (37°C, 98.6°F). This phenomenon, known as ebullism, results in severe dehydration of the human body (see Chapter 2).

The atmosphere has mechanical as well as physiological functional borders. As previously stated, at altitudes above 50,000 ft, oxygen must be supplied either in a pressure suit or in a pressurized cabin. At 80,000 ft, or 15 miles, cabin pressurization by compression of the ambient air becomes impractical. The air is so rarefied that extremely heavy compressors would be needed. Even if such a prohibitive weight could be carried, the creation of such high pressure differentials would result in an exorbitant amount of heat. Thus, compressing air from the ambient pressure at 100,000 ft altitude to a pressure equivalent to 10,000 ft altitude would raise the temperature of this air to 540°C (1000°F) (8). Hence, above 80,000 ft the cabin must be sealed off from the outside and be pressurized with interior gases.

As atmospheric pressure decreases so does the density, and the distance between particles increases. Since a medium of a certain density is a requisite for the transmission of sound, all sound will cease when the medium becomes rarefied to such an extent that the distance between its contained particles is comparable to the wave length of sound. Space silence occurs at an altitude of about 130 km (80 miles). Above this altitude, the Mach number * becomes meaningless.

The darkness of space also begins at about this altitude (10,11,12). Light travels through a vacuum, but diffuse daylight illumination occurs only if light is scattered by particles of the atmosphere. At 30 km (100,000 ft) the sky brightness is one-thirtieth of its value at 3 km (10,000 ft), and at 120 km (400,000 ft) it is about the same as a clear moonlit night at sea level. At 150 km (500,000 ft) the sky illumination approaches that of a moonless night. With the lack of diffuse illumination, stars become visible during the day, and any illuminated object will appear very bright against the black sky. The brightest stars are visible during the day at an altitude of 30 km (100,000 ft), and stars of the fourth magnitude become visible at 120 km. The darkness of space thus begins at about 30 km and is complete at 160 km.

The greatly decreased atmospheric density also influences temperature and heat equilibrium (1,10,11,23). At high altitudes, the temperature of the air, expressed as the average kinetic energy of its molecules, is high. In the atmosphere an object suffers collisions with these particles. Hence, transfer of energy occurs, and eventually thermal equilibrium is established. As the number of particles, and hence the number of collisions, becomes smaller, thermal equilibrium is no longer established in a finite period of time. As the density decreases, collisions, energy transfer, and heating by convection eventually become negligible. Above 130 km (80 miles) the temperature of an object is determined mainly by radiative heating (see Chapter 3). Frictional heating is also due to collisions with the molecules of the atmosphere. The velocity of the vehicle as well as the density of the atmosphere influence frictional heating. Thus, for a slowly moving balloon, heating by friction practically ceases at an altitude

* Since the speed of sound varies with the density of the air, and hence varies at different altitudes and temperatures, it is convenient to express supersonic speeds not in absolute units of miles per hour, but in multiples of the speed of sound at that altitude. Thus, Mach 4 is four times the speed of sound.

of about 29 km (18 miles). For a vehicle moving with escape velocity (7 km/sec, 5 miles/sec) this border is extended to 130 to 160 km (80 miles to 100 miles).

A meteorite travelling at about 20 km/sec (12 miles/sec) crosses this same border. Below 135 km (95 miles) the atmosphere is so dense that the meteorite is heated by friction to incandescence. Although some meteorites may penetrate to altitudes of 80 to 96 km (50 miles to 60 miles), they usually burn up at about 110 km (70 miles); an occasional one burns at 135 km (90 miles). At higher altitudes the full range of meteorites, which can both puncture and abrade a ship, will be present.

Air density determines not only temperature equilibrium and meteorite penetration, but also the aerodynamic lift and drag on a vehicle. Above 50 km (30 miles) navigation by control surfaces becomes impossible and aerodynamic lift ceases. This represents the altitude limit for airplanes. Higher altitudes can only be attained in balloons or by rocket propulsion. Beginning at 200 km (120 miles), air resistance and, hence, drag become insignificant. Here, a vehicle can stay in orbit around the earth for a significant period of time. At 240 km (150 miles) there is still enough drag on a vehicle travelling at 7 km/sec to bring it down in one day, but at 800 km (500 miles) it will stay in orbit several decades (19).

The atmosphere provides protection not only against meteorites, but also against space radiations. Selective atmospheric absorption shields inhabitants of the earth's surface from the sun's radiation, especially in certain biologically damaging regions of the electromagnetic spectrum. A band of ozone, located in the mesophere between 15 km and 40 km (9 miles and 24 miles) with a maximum at 30 km, absorbs solar ultraviolet between 2100 A° and 3000 A°. The ionosphere absorbs the shorter ultraviolet radiations and x-rays. Cosmic primaries, consisting of very fast, totally ionized atomic nuclei of the elements from hydrogen to iron, are absorbed by the atmosphere at an altitude between 21 km and 45 km (see Chapters 4 and 5).

Table 1.1 summarizes these space-equivalent regions. Some of the functional borders of space are as low as 10,000 ft, well within the troposphere; all are below 120 miles, or 200 km. This region between 2 miles and 120 miles is the region of partial space-equivalence, also named the aeropause (11,25). It is accessible to airplanes and balloons, and man has explored this region for over a century. Many of the problems to be encountered in space are no different physiologically from those met at space-equivalent altitudes. These conditions include anoxia, dysbarism, ebullism, and radiative heat exchange, which have been studied extensively by aviation medicine for years. However, there are other problems, both technical and physiological, which are unique to true orbital flight beyond the earth's atmosphere. These are mainly the problems of high