MEDICAL PROBLEMS INVOLVED IN ORBITAL SPACE FLIGHT

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BY

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Paper to be given at the Space Medicine Session, American Rocket Society Annual Meeting, at the Diamond Jubilee Annual Meeting of The American Society of Mechanical Engineers, in Chicago, Ill., November 13-18, 1955 at The Congress Hotel.

MEDICAL PROBLEMS INVOLVED IN ORBITAL SPACE FLIGHT*

OR

THE SPACE MEDICAL PROBLEMS

INVOLVED IN A MANNED ARTIFICIAL SATELLITE*

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For about six years Space Medicine, a branch of Aviation Medicine, has been studying the human factors involved in flights into the upper atmosphere and beyond, into space. There are various phases of this kind of flight, depending upon the physical and physiological characteristics of the environment, the speed of the vehicle, and upon the destination of the flight.

The first stage of space flight that we can expect in the immediate future will be the long distance flights as supersonic speed through the space equivalent regions of the upper atmosphere. These flights are the logical development of the present day long distance atmospheric flights on a global scale and can justly be called global or long distance space equivalent flights. With regard to motion dynamics, part of the time the vehicle exhibits <u>airplane status</u> and part of the time <u>projectile status</u>. We are now at the threshold of this first phase of space flight, namely, global space equivalent flight.

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A decisive phase in the development of flight will have been achieved as soon as the speed of about 5 miles per second or 18,000 miles per hour has been reached. This is referred to as the circular orbital velocity, the speed which enables a vehicle to circle permanently around the Earth in an orbit; such a vehicle takes on a satellite status, like the moon. This is circumplanetary space flight, or more specifically, circumterrestrial space flight.

As soon as a speed of 7 mps or 25,000 mph has been reached, the vehicle will break away from the gravitational control of the earth and escape into the depth of interplanetary space. This vehicle will then have attained spaceship status; this will be the final phase of space flight and can truly be called interplanetary space travel. The foregoing is a classification of the possible developmental stages in human flight, based on physical, technical, and medical considerations and refers to manned flight only.

It is my purpose in this paper to discuss the medical problems involved in the second phase of space flight, namely, that of circumplanetary space flight or satellite flight. This is full-fledged space flight in its simplest form. Full-fledged, because all of the strange environmental and motion conditions associated with space flight are encountered; in its simplest form, because the vehicle's movement is uniform and unidirectional. Circumplanetary space flight, therefore, is an especially suitable topic for discussion of the fundamental medical problems confronted in space flight.

The first step in the direction of this phase of space flight is the instrumented unmanned satellite, such as the one recently proposed, and to be ready for launching in 1957; but we will take a step further and assume, for the purpose of our discussion, an instrumented manned satellite. We will not, however, discuss how this vehicle arrives at its orbit and the medical (acceleration) problems involved - which are not insurmountable - but rather we shall presume to be at the stage where the vehicle has already reached a certain orbit and has attained satellite status.

The speed required to attain satellite status is nearly 18,000 mph near sea level. The denser regions of the atmosphere would prohibit this speed because of air resistance and friction heat. At about 120 miles or 200 km., however, the air is without noticeable effect in both respects. This aerodynamic and aerothermodynamic border of the atmosphere can therefore be designated with the more general term, astronautical border of the atmosphere. The actual material border or astronomical border of the atmosphere, however, reaches into the area of 600 miles or 1000 km. from where we enter through a 600 mile wide spray zone into interplanetary space. But it must be emphasized that even above the astronautical border, the atmospheric environment is space equivalent in practically every respect. It is here that the laws of aerodynamics lose their meaning and those of astrodynamics take effect, rather than at the astronomical border.

Above 120 miles, therefore, the nearest satellite orbit is conceivable. The orbital speed required at this level is roughly 17,500 mph and the period of revolution is about 88 minutes. Naturally, with increasing altitude, the orbital velocity decreases, and the period of revolution increases (see Table I).

Now, for our medical discussion, let us assume a ~~300~~ 1,000 <u>mile altitude orbit.</u> At this altitude we are beyond the F layers of the Ionosphere and far behond the astronautical border. At the 300 mile level the orbital velocity is 17,000 mph and the period of revolution 95 minutes.

Characteristic of the orbital velocity is the fact that the gravitational pull of the earth and the centrifugal forces caused by the vehicle's inertia, are balanced, which means that the vehicle and its occupants are in the state of <u>weightlessness</u> or <u>zero-gravity</u>. This is the first of the medical problems that I would like to discuss. There are two sides to this problem: 1) the <u>general medical aspect</u> regarding the well being of the occupants, and 2) the sensory physiological aspect concerning sensory perception of position of the body in space and senso-motoric control of the body movements. So far, experiments on man to study the effect of zero gravity have been carried out up to only 30 seconds in parabolic flight maneuvers in jet planes. The experiments of E. R. Ballinger in Wright Field Aeromedical Laboratory in 1952, those of H. von Beckh in Buenos Aires, Argentine in 1953, and most recently those of S. J. Gerathewohl in Randolph Field, Texas, do not indicate a serious disturbance in the autonomous nervous system which controls respiration and circulation. J. P. Henry, et al, on their recordings on monkeys in a V-2 and an Aerobee during a 3 minute period of zero gravity found no evidence of a significant disturbance of the cardiovascular or respiratory system. So far we have no proof that there would be any difference during a longer period of time such as would be found in a satellite. A possible shift in blood pressure due to the absence of hydrostatic pressure in the vessels might be easily regulated by the presso-receptors of the arterial system. It is therefore too early to speak of a "space disease" similar to motion sickness. At this point I would like to add that a manned artificial satellite is the only means of bringing about a final solution of this entire problem because it alone offers the possibility of experiencing the gravity free state for periods of days, weeks, and months, near the earth.'

As to the second or the sensory side of the gravity free state, this can be said: we have several sense organs, or specific nerve endings that serve as gravi-receptors, such as the centrally located otolith organ, and the receptors of the pressure sense distributed peripherally over the entire skin (about 20 per cm^2); specific nerve endings in the muscles, the so-called muscle spindles and finally, specific nerve endings in the connective tissue, the Pacinian corpuscles. They all belong to the category of mechano-receptors; these receptors have an exteroceptive function insofar as they react to external forces and inform us about the outer world. One such external force is the gravitational pull of the earth. They also have an enteroceptive or a proprioceptive function insofar as they inform us about the tension conditions in the skin, the muscles, and the connective tissue. They play, therefore, an important role in the sensory motor control of the body's movement. In the case of the vestibular apparatus and the pressoreceptors of the skin, the exteroceptive function is more pronounced, in the other mechanoreceptors the proprioreceptive function is dominant.

In the gravity free state the exteroceptive or the gravi-receptive function of the mechanoreceptors is eliminated; the proprioceptive function, however, is not. For this reason, a man making a high dive from a diving board, is able to perform a variety of acrobatic jumps quite skillfully, although he is in a gravity-free state throughout the dive. The absent gravi-receptive function of the mechano-receptors is substituted for by the exteroceptive sensory organ par excellence: the photoreceptors, or -- in other words -- the eyes. When in the gravity free state, as in a satellite, the eyes will be the only sense organ that informs the occupants of their position in space. This brings us to the problem of vision in space.

Of what kind are the light sources that confront us in Space?

Direct sunlight and starlight are first; we are also confronted by indirect sunlight coming from the earth, reflected by the continents, the oceans, and especially by the clouds. Moreover, some of the indirect sunlight is scattered from the denser layers of the atmosphere back into space. Finally, we have indirect sunlight reflected from the moon's surface. But there is no skylight, and this is the factor that makes the visual conditions so strange in the regions where satellites are conceivable. Skylight is sunlight scattered in all directions by the air molecules. Because the short wave part of the visible spectrum is especially affected, the scattering produces the diffuse blue daylight in the denser regions of the atmosphere, as it is observed from the Earth's surface. Against this rather bright skylight, during the day time the Moon and stars fade into invisibility. With increasing rarification of the air molecules in higher altitudes, scattering of light diminishes gradually and ceases at about 100 miles. Beyond this level the sky is permanently dark.

The extra-atmospheric sky brightness is only 10 millilambert as compared with that of 500 millilambert in the lower atmosphere. But the sun is visible in its full brilliance against the dark sky, except of course when the satellite moves through the shadow of the Earth. The stars are also visible all the time, and when its position allows, the moon can be seen in full light intensity together with the sun. Because of the lack of skylight in space, the contrast between light and darkness is a dominant feature. Everything that is exposed to sunlight appears in full brightness and vivid color, and everything else is in the darkness of shadow. The extra-atmospheric illumination is around 13,500 foot candles as compared with 11,800 foot candles at the Earth's surface. Light and shadow dominate the scenery comparable to the light and shadow effects such as those produced on the stage for the magician. This strange photoscotic condition poses medical problems in the field of contrast vision and retinal adaptation. And the strange distribution of the light sources, Sun, Stars, and the indirect sunlight from the earth and moon are of special interest from the standpoint of orientation in Space.

At this point I would like to make a comparison with an environment that is, so-to-speak, the extreme opposite of that found in space; namely, the deep sea. In the environment, there are also some similarities that, according to the well-known proverb "less extrême se touche."

W. Beebe observed in his "bathysphere" that the light intensity decreases rapidly with increasing depths, while the spectrum shifts towards blue-violet. But at a depth of 1600 feet, light is completely absent in the Atlantic ocean. In these regions we find fish with luminous organs and telescopic cylindrical eyes. At depths of about 10,000 feet there are fish with only vestigial eyes. These deep sea fish rely almost entirely on the mechano-sensory system of their skin to sense the environment. This represents an extreme contrast to the situation that will be experienced by man under space conditions. In the darkness of the deep sea, where the photoreceptors are out of function, the position and movement of the fish is controlled solely by the gravi-receptors and mechano-receptors; in the darkness of deep space and under the conditions of gravitational orbital flight where the gravi-receptive function of the mechano-receptors is eliminated, orientation depends entirely upon the photoreceptors or upon vision. The sun, the stars, and the earth and moon are the optical footholds for the visual orientation in space.

The observation of the sun, however, poses an important medical problem. The brilliant radiance of the sun in its original intensity, while not affected by atmospheric absorption, represents a hazard to the eyes. A much shorter time of exposure is sufficient to cause a retinal burn, such as that known to the ophthalmologist, as it occurs occasionally when someone observes a solar eclipse through an insufficiently smoked glass. Such a solar radiation effect upon the fovea of the retina is demonstrated in Picture 2 which shows a small distinct spot of altered tissue. This is a picture of the retina of my right eye, which shows a retinal injury which I acquired when I observed a total solar eclipse in 1911 as an inexperienced space-curious boy of twelve. The result of such a so-called eclipse blindness is a scotoma or a blind spot in the visual field. Outside of the atmosphere, the danger of such a retinal injury by direct solar light is much greater and from an artificial satellite the sun should be observed only through glass with very high absorptive power.

In connection with the optical conditions found in the space equivalent regions of the atmosphere beyond 120 miles, and in interplanetary space, I would like to bring to your attention a physiological problem that has never been touched upon in space medical discussions. It is the problem of maintenance of an adequate physiological day-night cycle for the occupants of a space vehicle.

In space flight, such as that in a satellite, the concept of night loses its meaning and must be replaced by that which night really is, namely, the shadow of the earth.

The shadow or umbra of the earth tapers down in the form of a cone 859,000 miles or 1,383,000 kilometers deep into interplanetary space. Travelling through the greatest width of this sunless dark cone would take our assumed satellite less than 40 minutes. During the remaining part of the revolution (about 55 minutes) the vehicle is exposed to the sun and surrounded by darkness at the same time, as described hereinbefore. Such are the optical conditions if the satellite orbit passes through the earth's shadow.

Many different kinds of orbit planes, however, are conceivable; in some of them a satellite would not touch the umbra at all. Be that as it may, in orbital space flight an adequate ambient physical day-night cycle is absent because the day-night, or more precisely, the light-shadow cycle is less than two hours. Therefore, we must create and maintain an artificial day-night cycle within the satellite to meet the physiological requirements of the occupants. For, adequate diurnal cycling is of great importance to the health and efficiency of man. In fact, we are so strongly adapted, or so physiologically bound to a day-night cycle, manifested in rest or sleep and wakefulness or activity, that it must be regarded as a biological law. To ignore this law would, after a week or so, lead to a complete nervous breakdown.

How can an adequate day-night cycle be achieved for the occupants of an artificial satellite?

For them, the night time must be induced in a special night compartment. The question is posed as to the length and time interval of such an artificial day-night period.

In this regard reference is made to the important basic experiments carried out in the Mammouth Cave in Kentucky, 1940, by N. Kleitmann, Professor of Physiology at the University of Chicago. Dr. Kleitmann spent two months in this cave, with several co-workers, under artificially produced day-night cycles of different lengths. The result of these experiments showed that man can adapt himself to a diurnal cycle only in the range of from 18 to 28 hours. Within this range the temperature curve of the body follows the various cycles. When a cycle, shorter than 18 hours or longer than 28 hours, was introduced, no adaptation was possible and the temperature curve returned to its normal cycle of 24 hours.

This gives us the clue for solving the problem of diurnal cycling in a manned satellite. If we choose a minimum day-night cycle of 18 hours, dividing it into 8 hours for sleep, 2 hours for recreation, and 8 hours for duty, that would be a reasonable solution. Or, if a 24-hour day-night cycle is selected, the best plan for a subdivision of this cycle would be 8 hours for sleep, 8 hours for rest and recreation, and 8 hours for duty. All this presupposes that the crew will be large enough to be subdivided into three groups. In the case of an artificial 18 hour day-night cycle, a two-group crew would be sufficient for a manned satellite operation.

We may assume that the metabolic rate of an occupant of an artificial satellite during his duty hours, is about the same as that of an occupant on Earth during moderate work; the total metabolism during a 24-hour period, including sleep and recreation would then be in the order of 2,500 cal. for a 70 kg. Man. This brings us to the respiratory requirements for the satellite crew, or more generally speaking, to the climatization of the cabin. The cabin in a satellite must of course be completely closed, a sealed cabin, in which an adequate atmosphere is artificially created and controlled. It must be emphasized, however, that such a type of cabin is required even down to the atmospheric region of 70,000 to 80,000 feet.

One of the vital tasks in the climatization of the sealed cabin is the solution of the oxygen problem for respiration.

From the aforementioned metabolic rate of 2500 cal per man per day, we can calculate the amount of oxygen required by one man per day. The caloric equivalent of 1 liter of oxygen is 4.85 under normal nutritional conditions. This means that the biological production of 1 cal. requires 206 cm^3 of oxygen. Consequently, the total amount of oxygen consumed per man per day is roughly 500 liter or 0.7 kg. This amounts to 46 kg. of oxygen per man for 1000 satellite revolutions that take place in 66 days in our assumed orbit at the 300 mile altitude, or 276 kg. O_2 for a crew of six. Replacement of the consumed oxygen from the storage tanks must be controlled in such a way that the oxygen pressure does not fall below 100 mm Hg. This is about the minimum limit permissible for comfort and efficiency; it should not surpass the permissible maximum of about 300 mm Hg because O_2 concentrations above this level are toxic. The fact that we can tolerate a rather wide variation in oxygen pressure (from 100 to 300 mm Hg) facilitates considerably the oxygen problem in space flight.

Whereas oxygen is consumed in the metabolic processes of the body cells, carbon dioxide is produced in the same process and exhaled. Under normal nutritional conditions the ratio between exhaled carbon dioxide and consumed oxygen, the so-called respiratory quotient is 0.85. With our example, one man produces 425 liters of carbon dioxide or 0.837 kg. per day or 55.2 kg. per 1000 satellite revolutions. This would be 331.2 kg. for a crew of six. Carbon dioxide in concentrations above 4 vol percent is toxic; the permissible limit lies at about 1 vol percent under standard barometric pressure or at about 8 mm Hg. The removal of the excess carbon dioxide in the sealed cabin vehicle, which can be achieved by certain chemicals or in a physical way is, therefore, just as vital as the maintenance of an adequate oxygen pressure.

Since the consumed oxygen appears again in bound form, namely within the carbon dioxide of the expired air, it has been suggested to try to regain the oxygen from the carbon dioxide, in this way eliminating a toxic gas and at the same time facilitating the problem of oxygen supply.

A natural method accomplishing this, is known to us in the process of <u>photosynthesis</u>, found in chlorophyl bearing plants. Photosynthesis is the reverse process of respiration as a comparison of their reaction formulas shows:

Respiration: $C_6O_{12}O_6 + O_2 \longrightarrow 6CO_2 + 6H_2O + \text{Energy}$

Photosynthesis: $6CO_2 + 6H_2O + \text{Solar Energy} \longrightarrow C_6O_{12}O_6 + O_2$

In respiration or biological oxydation, oxygen is consumed and carbon dioxide and water are produced. This process requires several so-called respiratory enzymes. In photosynthesis oxygen is produced and carbon dioxide and water are consumed. This process requires the presence of chlorophyl as an activator.

In special studies sponsored by the USAF School of Aviation Medicine, it has been found by Prof. Dr. Jack Myers, Head of the Department of Algal Physiology, University of Texas, Austin, Texas, that 2.3 kg. fresh weight of a certain alga - the alga chlorella pyrenoidosa - with regard to gas metabolism, under optimal conditions, are equivalent to one man. This means that this mass of algae consumes as much carbon dioxide and produces as much oxygen per time unit as one man produces carbon dioxide and consumes oxygen during the same period of time. Both, therefore, could live together and support each other with regard to the respective respiratory and photosynthetic requirements in a symbiotic-like state, in a closed system for a considerable length of time.

Plants like the alga chlorella are especially suitable as a photosynthetic gas exchanger. They are small round bodies about the size of red blood cells and are dispersed in a nutritional solution. These primitive plants are perfect photosynthetic machines, since they have no specific organs nor various functions like the higher plants. Their only function is to build up carbohydrates and to produce oxygen photosynthetically. Primitive plants of this type already appeared on this planet one and one-half billion years ago. And they might have been responsible for an early build-up of an initial stock of oxygen in the primitive atmosphere or protoatmosphere of the natural satellite of the sun, namely, the earth. And now, the same biological process may some day be used in the climatization of artificial satellites of the earth. But the difficulties for the use of such photosynthetic gas exchangers lie in the volume and weight of the device, in the arrangement of and in the power requirement for illumination. As for the latter, solar energy may be the answer. For flights of short duration, however, we certainly will never resort to a biological gas exchanger. For flights over weeks and months it might be different. Maybe some day we will have a type of photosynthesis that can utilize infrared, or, the efforts that are made to achieve artificial photosynthesis may one day be successful.

In the sealed cabin also, the moisture given off - in amounts of from 50 to 80 gram per man per hour through respiration and perspiration under comfortable temperature conditions by the occupants, must be kept within the comfort limits that range between 30 and 50 percent relative humidity. And finally, the barometric pressure should be kept at levels corresponding to that found near sea level and up to 9,000 feet. In this respect, however, the physiologist could make concessions to the engineer, who for structural reasons would probably desire a lower pressure differential between the cabin's air and the surrounding near vacuum. From the physiological point of view a minimal barometric pressure, corresponding to an altitude of 15,000 feet would be acceptable.

The multitude of factors involved in the climatization of the sealed cabin requires a complex of instrumentation for automatic control.

The USAF School of Aviation Medicine, Randolph Field, Texas, now has an experimental sealed chamber in which we can study the changes of the atmospheric conditions caused by the presence of the occupants, and the means to control these factors. Fig. 3. This device can also serve as an indoctrination chamber in handling the situation in case the automatic controls fail or the cabin develops a leak.

With this point we touch upon the Achilles' heel of the sealed cabin vehicle. One of the causes of a leak might be a collision with a meteor, a probability which is very remote; however, the occupants of a satellite vehicle must be prepared for such an event, even though meteor bumpers or screens - suggested by F. Whipple and others - might offer effective protection.

In the lower atmosphere, the time rate of decompression of the pressurized cabin is governed by three factors: the volume of the cabin, the size of the hole, and the barometric pressure of the ambient atmosphere. In a satellite vehicle, the latter factor is practically zero, which means that under other equal conditions the decompression will be more violent and faster. In any event, the crew must know that a drop in oxygen pressure to 100 mm Hg. will effect their efficiency, as aforementioned, and that at 60 mm Hg. the situation will become critical and dangerous. Before this critical level is reached, the source of the leak must be sealed, otherwise, the crew would face the whole physiological sequence of decreasing air pressure effects.

These are some of the medical problems encountered in manned satellite flight. I have not touched upon the radiation problem, which has been discussed in the paper of Major David G. Simons.

All of the space medical problems discussed so far are also encountered in transfer orbits, that is, in interplanetary Space Travel. They will be faced also, more or less, during a certain portion of space equivalent flights, that is, in long distance flights at hypersonic speed through the space equivalent regions of the atmosphere. But we find them, so-to-speak, in classical form in circular orbital flight or in a satellite vehicle. The unmanned instrumented satellite planned by the United States for launching in 1957 or 1958, will be the indispensible exploratory forerunner of the manned satellite, which will certainly come some day.

Be that as it may, the main reason that I have chosen this phase of space flight in this paper was that a satellite vehicle offers an ideal platform for the discussion of the problems of space medicine in general and for giving you an up-to-date picture of the progress made by this fast developing branch of Aviation Medicine.

LEGENDS

Fig. 1 – Orbital velocities and periods of revolution of an artificial Earth satellite at various altitude levels.

Fig. 2 – Retinal injury of the eye caused by observing a solar eclipse through an insufficiently smoked glass.

Fig. 3 – The experimental sealed chamber of the USAF School of Aviation Medicine, Randolph Field, Texas.

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HEIGHT MILES	ORBITAL VELOCITY M P H	PERIOD OF REVOLUTION MINUTES	HEIGHT KM
1000	15,788	118.5	1600
800	16,116	111.3	1280
600	16,466	104.5	960
500	16,649	101.1	800
400	16,839	97.7	640
300	17,035	94.4	480
200	17,238	91.1	320
120	17,449	87.8	182
NEAR SEA LEVEL	17,668	84.6	NEAR SEA LEVEL