Beyond the moon—some problems in space medicine¹

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In April 1971 we will enter the second decade of manned space flights, and on the threshold of this second decade there is a striking disparity between our treatment of man and our treatment of the complex systems which comprise the spacecraft-launch vehicle and supporting equipment. The fantastic sophistication resulting from our dedicated pursuit of improvement in the engineering of electronic and mechanical systems has not been matched by our capability to utilize man or our understanding of how man is affected by the space environment.

In 1967², the President's Science Advisory Committee issued a report entitled 'The space program in the post-Apollo period'. Exploration by man of the nearby planets was identified as the most challenging ultimate objective for space exploration. However, the role that man might play on such a mission is not clear. Despite all of the oratory and controversy on this subject, it is virtually impossible at this time to assign to man the exact role he would play in planetary flights. That is why a manned planetary mission should not be considered as a programme commitment at this time.

But what of other missions which may be considered as feasible before manned planetary exploration and again, can man's role be defined? One major class of mission, the performance of scientific experiments in space, must develop eventually in a form that will escalate man's ability to handle demanding tasks vital to mission success. Thus, the post-Apollo period should be the period concerned with the manned orbital laboratory or manned space stations. What is it that we want to know? There are many factors involved, ranging from criteria for crew selection and the particular talents required to the effects of prolonged weightlessness. Three critical questions could be answered by prolonged manned flight in earth orbit. One, can man survive in the space environment for several years? Two, beyond survival will he continue to perform effectively and

will the fundamental knowledge gained about him and the technological effort involved in assuring his effectiveness attest to the feasibility of manned interplanetary flight? Three, what concepts of components and systems design will prove most useful in enhancing man's effectiveness, and, equally important to increase the overall reliability of the systems? Qualification of man for flight prolonged beyond the maximum of 14 days will require special consideration of his ability to perform for indefinitely long times at a high level both mentally and physically. While no definite period of exposure to the space environment can now be set as a criterion for qualification of man for flights such as those to a nearby planet covering a round trip of perhaps two years, it seems likely that a test of from 100 to 200 days in earth orbit would reveal most or all physiological disorders likely to be deleterious to mission performance.

Acceleration

There may be acceleration exposures which become so severe that they produce major physiological or psychophysiological disturbances. The spectrum of acceleration environments is extremely large and may vary in duration, magnitude, rate of onset and decline, and direction. The unit commonly used for physiological acceleration is *g*. Forward acceleration moving in a transverse, anterior-posterior direction or chest to back is known as 'eyeballs in'. Backwards acceleration moving in a transverse, posterior anterior or back to chest direction is known as 'eyeballs out'. Upward acceleration directed towards the head is known as 'eyeballs down' while downward acceleration towards the feet is 'eyeballs up.' Acceleration to the right or right lateral acceleration is called 'eyeballs left' while the 'eyeballs right' position implies a left lateral acceleration. The use of a comparative nomenclature and the colourful eyeball terminology has obvious usefulness. The astronauts begin their journey while acceleration *g* forces are building up in the launch vehicle. With ignition of the rocket engines millions of pounds of

¹This is a slightly shortened version of the annual Sir Roy Cameron lecture given on 6 May 1970.

²President's Science Advisory Committee Report (1967). *The Space Program in the Post-Apollo Period*. U.S. Government Printing Office, Washington, D.C.

thrust literally hurl the astronaut out of the earth's gravitational field into space. On re-entry acceleration again becomes an important factor as the g forces build up for appropriate insertion into the earth's atmosphere. It would appear that the heart is one of the most vulnerable organs, with changes in anatomical relationship within the thorax as a consequence of g forces. The duration in g load will vary from mission to mission. Acceleration profiles will be different for each booster stage during which the acceleration is continually changing.

To study the physiological effects on earth experiments have used man and chimpanzees on a missile track and in a centrifuge. The human centrifuge has been an invaluable tool in studying the effects of g forces along various axes or vectors of action. For example: upward or headward acceleration is associated with a redistribution of blood influencing first the perfusion of blood through the subject's eyes and brain causing loss of vision, blackout, and loss of consciousness respectively. Astronauts are rigorously trained in the centrifuge for this builds up tolerances to the deleterious effects of the various g forces. This is extremely important if during a particular mission acceleration of the vehicle either on its own or by external forces becomes abnormal. With a slow increase in magnitude towards 2 g an increase in weight is observed by the increased pressure on the buttocks in the seated position and drooping of the soft tissue of the face and body. By 2½ g it is nearly impossible to raise oneself and by 4 g the arms and legs can hardly be lifted. Hydrostatic effects manifest themselves in the relaxed, unprotected subject in the seated position after about three seconds' exposure to 3 or 4 g , with progressive dimming of peripheral vision. Vision is tunnelled at 3½–4 g with complete loss of vision or blackout at 4½ to 5 g after a total plateau exposure of about five seconds. Hearing and consciousness are retained for a few seconds longer but are finally lost. In one study, 50% of the subjects showed mild to severe convulsions during the unconscious period and recovery is frequently accompanied by bizarre dreams. Blackout and unconsciousness are sometimes associated with paraesthesia, and confused states but no incontinence was observed. Pain is not normally a feature but the lower portions of the legs feel congested and tense. There may be muscular cramps and tingling. If unconsciousness occurs, a loss of orientation for time and space persists for about 15 seconds after cessation of acceleration. Changes in the gaseous environment of the space vehicle alters tolerance to g forces, especially where thoracic dynamics are modified, so that the work of breathing is increased and pulmonary volume, pressures, and fluids shift. Collapse of a lung segment or atelectasis

are seen on radiographs, and, as the pulmonary vascular pressures rise, there may be focal haemorrhages and oedema.

Devices for protection against positive accelerations have been developed by various laboratories. The Russians have studied cerebral blood volumes and cerebral blood flow during various acceleration forces. Others have observed that cerebral function is completely impaired between 3 and 8 g in the headward direction. In the other vectors the subject normally reaches a tolerance threshold of another sort before unconsciousness occurs. On return to consciousness, there is usually a short period of confusion. Changes in the EEG have been observed. Performance, body movements, tracking tasks—all critical to the success of the mission—are at stake. What if a space vehicle is subjected to a tumbling effect or if suddenly during extravehicular activity the astronaut begins tumbling in space? When tumbling is added to an acceleration field the result is not merely the summation of responses but at least at rates of rotation below 100 rpm the influence of the deceleration field appears paramount. Though adequate quantification of this fact is lacking in studies in human subjects, postmortem studies of animals exposed to variable acceleration up to 35 g and rotations of 30 to 150 rpm in different attitudes show, one to six hours after exposure, tissue damage in most of the internal organs characterized by vascular congestion, oedema, haemorrhage, hyaline thrombi, and separation of parenchymal cells in solid organs. Very little is known about the upper limits of human tolerance to simple tumbling or tumbling in a decelerative field. Most of the studies have involved animals.

Very little is also known about the effects of spin or rolling. A mixed roll and yaw manoeuvre occurred accidentally in the Gemini VIII flight. Within a few minutes after docking the orbit attitude and manoeuvre system (engine no. 8) initiated without command a series of sustained firing periods of varying lengths. These energy impulses caused the two joined vehicles to begin a lengthy period of uncontrolled manoeuvring, predominantly in the roll mode. The firing of only one of the eight yaw roll engines, as occurred in the accident, resulted in a combined yaw roll manoeuvre by the spacecraft. The astronauts attempted almost immediately to stop the motion and decouple the two vehicles. However, due to disorientation resulting from vestibular-ocular disturbance, their efforts to regain stability were seriously impaired. Astronaut Armstrong's pulse reached 156 and his performance was degraded. Significantly, astronaut Armstrong was quoted as having said in debriefing interviews that during the emergency of Gemini VIII he could not

'see' the circuit breakers which controlled the malfunctioning rocket engine. These breakers were located above his eye level. Apparently, in response to Armstrong's report the circuit breakers were relocated on the instrument panel for Gemini IX and subsequent flights. Whether his problem was due to image slipping or induced nystagmus resulting from head movement is not clear. Nevertheless, impaired vision is to be expected during accelerated rolling. Several less than optimum decisions were made, one of which, firing engines in both of the redundant re-entry control systems, necessitated an immediate abort of the mission at an unfavourable landing site. A variety of simulators and various programmes have been developed to explore further the problem on earth. The vestibular interactions in the rotary environment are extremely important.

With House, Pansky, and Jacobs (1964)¹ we studied in detail the middle ear of the chimpanzee. One animal served as a control and a second had been subjected to ejection while hurtling along the 7 mile missile track. Because of the unique features of the chimpanzee skull—the positioning of the semicircular canals and the membranous sacs housing the utricle and saccule—extrapolation to man was difficult if not impossible. Physiological studies had shown a peculiar resistance on the part of the chimpanzee to the kinds of acceleration, rolling, and spinning forces that have been described for man.

Obviously, much of this information is also important in setting operating limits for proposed rotating space stations. The basic problem is one of maintaining the angular velocity at a tolerable maximum with a spin radius adequate to keep the g level within satisfactory ranges.

Zero Gravity Environment or Weightlessness

Zero gravity or weightlessness has been the object of many speculative and empirical studies. Data are now available on physiological and performance responses in orbital flights of up to 14 days' duration. Responses to weightlessness may be classified as cardiovascular, respiratory, metabolic, and psychomotor. Most observations of cardiovascular responses of astronauts exposed to weightlessness have been made in the immediate postflight periods. Cardiovascular data for American missions up to 14 days and Soviet missions up to five days have been reported. However, these findings must be viewed with caution. Confinement, limited physical activity during missions, and postflight fatigue are factors affecting the cardiovascular system similar to those which have been predicted for weightlessness. On

occasion, postflight data may also have reflected the effects of dehydration and physiological events which are associated with the vague feeling of let down often experienced after a prolonged emotionally and physically stressful event. In studies of up to 42 days of bed rest, seven days of complete immersion in water, and 14 days of weightlessness in space, recordings of systolic and diastolic pressures, pulse rate, heart sounds, and ECG have remained within normal limits, even in the face of marked physical inactivity which led to diminished exercise tolerance. Soviet studies of bed rest for up to 20 days have shown somewhat wider but not serious cardiovascular changes, called the 'myocardial hypodynamic syndrome'. It appeared unlikely that prolonged weightlessness would significantly alter cardiac function if cardiac work capacity was maintained through physical exercise while in orbit.

Cardiovascular adaptation to prolonged weightlessness results in lowering of blood volume with decreases in both the plasma and red cell fractions of the blood. Postflight data on the command pilots and pilots of the four- and eight-day Gemini missions indicated that the blood volume also decreases in both the plasma and red cell fractions of the blood. A decrease of blood volume of 7 to 15% occurred during these missions. The decrease in plasma volume was 4-13%. A weight loss, usually of 2 to 5% of body weight, recorded after space missions may be due only in part to duration of the mission or plasma volume, a surprising circumstance, and preflight weight and plasma volumes were restored rapidly by fluid intake in the postflight period. Immediately after the 14-day Gemini mission the blood volumes of both astronauts were the same as those recorded before the flight.

Removal of the gravitational component of intravascular hydrostatic pressure leads to a headward redistribution of blood. Central venous channels are distended, leading to stimulation of central venous blood volume receptors located mainly in the right atrium. Through reflex pathways antidiuretic hormone production is probably inhibited. The resulting increase in plasma water excretion re-establishes normal central venous volume. Due to one or more possible mechanisms involving venous and possibly arterial volume sensors as well as osmoreceptors aldosterone production is suppressed leading to a variable diuresis with sodium excretion. The constancy of osmotic composition appeared to be sacrificed in favour of the constancy of blood volume. There is no evidence of a diuretic factor appearing in the blood, and renal haemodynamics do not seem to be altered to a significant degree. One result of the loss of blood and extravascular volume is orthostatic intolerance. This has been shown after

¹House, L., Pansky, B., Jacobs, M., and Wagner, B. (1964). *Middle Ear of the Chimpanzee*. U.S.A.F. Tech. Rep. ARL-TDR-64-1.

space flight as well as after water immersion and bed rest simulation. Exposure to a tilt-table test, a provocative test of orthostatic intolerance, results in an excessive increase in heart rate and excessive narrowing of pulse pressure and a fall in systemic arterial blood pressure while passively maintaining the erect posture. Failure of cardiovascular compensation to gravity leads to the so-called vaso-depressor reaction, the manifestations of which are presumably due to an overwhelming increase in parasympathetic nervous system activity. This reaction is characterized clinically by pallor, nausea, dimming of vision, sweating, and air hunger. It may eventually lead to loss of consciousness arising from an acute fall in systemic arterial blood pressure occasioned by bradycardia and a decrease in peripheral vascular resistance. We do not know with certainty what cardiovascular adaptations to simulated and actual weightlessness might have occurred to account for the decreased orthostatic tolerance that resulted from exposure to these conditions. The overall effects of weightlessness in the cardiovascular system have been referred to as deconditioning. Much more data are needed on the mechanisms which maintain cardiovascular integrity. However, prevention of these cardiovascular and fluid adaptations to weightlessness may be accomplished by the following activities in space flight: exercise, the judicious use of pressure cuffs or pressure suits, acceleration forces, and pharmacological agents. The accelerative forces would be those that would create an artificial gravity in space. This can be accomplished in one of two ways: if we are dealing with a space station then an on-board short radius centrifuge which would serve to spin the astronaut would be of value. Others have actually suggested a trampoline on which astronauts could bounce. Pharmacological agents that have been advocated include aldosterone, antidiuretic hormones, and plasma expanders. Already designed is a centrifuge for the 260-inch diameter manned orbital laboratory which can accommodate two men. The centrifuge can provide up to 1 *g* for therapeutic purposes and as high as 9 *g* for re-entry simulation while in space.

Respiratory Effects

The effects of weightlessness on respiratory function shows no gross defects other than a slight alteration of the normal vertical pressure gradient in the lung. However, in a weightless state, microparticulate matter floats within the space cabin and unless there is an adequate cleansing of the air could present a problem associated with prolonged inhalation of these particles.

Bone and Muscle

The lack of gravitational stress on bone and muscle is a major deconditioning factor in zero gravity. The obvious changes include rapid demineralization of bone with mobilization of calcium and loss of muscle bulk and tone. However, current experience indicates that with appropriate exercise and dietary intake of calcium, decalcification of bone should not be a major problem in future space flights. Control of dietary factors other than calcium, which are related to the maintenance of bone in optimum functional states, needs further study. The maintenance of muscle tone and bone density by exercise has been considered and is being actively used in the space programme.

Water and electrolyte excretions during Gemini flights have been studied and correlated with post-flight plasma or serum electrolytes. Immediately after a flight sodium was retained so its excretion was sharply diminished. Then, a short time later, there was a marked rise in urinary sodium levels as the retained sodium was being excreted. Urinary excretion of chloride paralleled that of sodium. The amount of potassium excreted in the urine during the 14-day in-flight period was significantly less than the amounts excreted either before or after the flight. Postflight water and sodium retention was attributed to the elevation of aldosterone output and it was postulated as a compensatory mechanism for increased water and sodium excretion during early weightlessness. The cause of the elevation of aldosterone output during midflight is not clear.

Vestibular Reactions

The effect of zero gravity in eliminating the chronic 1 *g* output for the otolith organs might be expected to produce the symptoms of vertigo and motion sickness because of the alterations produced in sensory interactions. However, the otolith organ responds to changes in acceleration. American astronauts while in orbital flight have been relatively free of nausea, vomiting, or serious illusory phenomena even during movement of the head. Careful crew selection and training and the relative stability of the spacecraft may have been important factors. Soviet experience in this area has been variable. Titov, who was an experienced acrobatic pilot and given preflight vestibular training, developed unpleasant sensations in Vostok II which he described as being similar to the sensation of being rocked back and forth. These gave rise to vertigo and dimming of vision. Nicolayev and Popovich in Vostok III did not become ill, but had sensations of travelling upside down on shift from acceleration

to weightlessness. Soviet reports indicated that the vehicle rotated on its axis at a rate of one rotation every 20 to 40 seconds. In Vostok VI, Terishkova reportedly experienced a psychotic episode which lasted for several days after the flight. There are several references to psychotic behaviour with full-blown hallucinations and delusions in the Soviet literature on weightlessness. On the basis of these and other data, Ugarov considers weightlessness under the unfavourable factors of space flight requires serious studies by physicians. In Soviet flights, handwriting and other complex psychomotor tests, involving high frequency tracking responses, showed improvement with time in orbit and even a better performance than under a 1 *g* acceleration.

Extravehicular Activity

One of the early discoveries by astronauts performing extravehicular activity was the dominant effect of small forces in the weightless environment. Each small force exerted by the astronaut resulted in a displacement velocity which in most cases interfered with the task he was attempting to perform. It was not until several hours of extravehicular experience in the space environment that appreciation of these factors was achieved. A major part of the effort was due to the pilot working against the pressurized space suit. Unless the astronaut was adequately restrained, his capability for useful work during extravehicular activity was severely limited. The Apollo 13 mission was to have tested seriously the ability of astronauts to work usefully on the surface of the moon. There, working in a 1/6 *g* field with a firm underfooting, the astronauts should perform better than if they were floating in space. Man must learn to work outside his vehicle in space in order to inspect the vehicle and make necessary repairs. Continued investigation in this area of research is in progress.

Performance of Tasks

Performance of tasks on the lunar surface is complicated by several factors beyond that of subgravity. Inflated space suits degrade performance of vehicle maintenance and other tasks in the subgravity environment. The light environment is also most unfavourable, with glare, shadows, blinding reflections from tools, suits, and vehicular structures. Little attention has been devoted to a study of performance aids required to facilitate lunar maintenance and operational tasks. This is one of the important missions of the Apollo programme. In attempting to predict the time allotted for any given task on the surface of the moon, the effect of the

lunar visual environment on performance becomes important. Our best estimate to date indicates that control tasks to be performed by astronauts on the surface of the moon will require approximately 100% more time than is required by the shirtsleeve operator in 1 gravity. It is also anticipated that the astronaut will lose time in finding a favourable position with respect to sunlight direction. Energy expenditures during the first Apollo 12 moon walk were lower for each man than the expected 1,100-1,200 BTU per hour. The energy expenditure is estimated from the constantly monitored heart rate of the astronauts. The heart rates of Conrad and Bean stayed mostly between 100 and 150 beats per minute during their first lunar exploration. They remained on the lunar surface for approximately four hours and yet each man had 30% more of his oxygen and water supply remaining by the time they returned to the lunar module and closed the hatch.

Radiation Research

Radiation research has been directed towards (1) the development of appropriate dosimetry for use in manned spacecraft to determine the radiation exposure of the crews; (2) the definition of the complete radiation environment exterior to the spacecraft; and (3) measurement of doses and dose-rate profiles in realistic geometries at the altitudes of interest.

One of the most difficult problems has been that of developing an adequate tissue equivalent dosimeter for use as operational equipment aboard manned spacecraft and for radiologically orientated unmanned satellites designed for space research. The available techniques are severely limited by spacecraft restrictions. All Apollo flights carried active dosimetry in the form of ionization chambers which were hard mounted to the spacecraft. This mounting arrangement makes it difficult to extend the ionization chamber data to doses received in various locations of an astronaut's body. Selecting the proper mounting locations for operational dosimetry within a manned spacecraft is difficult. Both the United States and the Soviet Union have employed passive dosimetry packages within the space suits or constant-wear garments to measure astronaut surface doses. A surface measurement is adequate when the doses are no higher than those yet encountered. But when higher doses are possible both a surface and depth measurement are required. The Russian and American data show that the distribution of radiation doses in the spacecraft and in the astronaut could be very important in determining the radiation hazard. Radiation dose measurement made on several Gemini flights show that the

radiation field within the spacecraft was not uniform and varied by more than a factor of 2 in intensity. Dosimeters placed close to the walls on one Vostok flight recorded doses two to three times higher than in the centre of the cabin. This effect was caused by secondary corpuscular radiation with energies in the order of 10 MEV/nucleon which was predominant near the spacecraft walls. Data both from manned and unmanned satellites showed that the largest uncertainty in the calculation of the dose was consistently in the radiation environment. A great deal more information is required. Suffice to say that both the American and Russian astronauts to date have not been exposed to kinds and doses of radiation that could be considered damaging.

The Biosatellite Programme

For many years, space biomedical scientists have advocated a programme utilizing primates in space. In 1969 biosatellite III with a male Macaque monkey was sent into an earth orbit for a 30-day period. The purpose was to evaluate in a comprehensive manner the effects of prolonged weightlessness on the central nervous, cardiovascular, and metabolic systems of the primate. The flight lasted only eight and a half days due to the physiological deterioration of the monkey. Important signs of pathology first appeared in the early days of the flight associated with a vestibular ocular disturbance. The monkey consumed food and all water offered until day eight of the flight, when the animal's condition deteriorated sharply. Food and water were no longer taken during this period and the heart rate slowed to 70 beats per minute, with a sharp drop in blood pressure. There was a slow fall in brain temperature to 35°C compared with 38.2°C at launch. Recovery occurred in the vicinity of Hawaii, eight and a half days after launch and the capsule was opened approximately three hours after re-entry. The monkey was cold and vital signs were scarcely perceptible. Careful resuscitation was attempted with blood transfusion, intravenous fluid, and electrolytes. The monkey's general condition improved and 12 hours after recovery brain temperature had risen and the brain wave record resembled that of light sleep. At this stage there was a sudden onset of ventricular fibrillation and further attempts at resuscitation were unsuccessful. At necropsy, no major pathology was

detected. There were small bruises on the liver and heart, both of recent origin and attributed to re-entry. From all studies available, it would appear that the circumstances leading to the animal's collapse were due to weightlessness as a prime factor, and are relevant to man as regards environmental constraints, task requirements, and mission duration. The critical measurement from this study in relation to manned flight is the finding of a high fluid loss even in a sedentary resting subject. This loss is related to shifts in blood volume and its distribution, with secondary changes in body fluid balance, electrolyte metabolism of sodium and potassium, and ultimately the stability of the cardiovascular system. There was an early and profound loss of fluid by insensible perspiration up to day 4. The urine output increased steadily to almost diuretic levels by day 8 of flight. This suggests a need for a guarded approach to design a mission for man that might involve extreme effort after a considerable exposure in weightlessness. There are many who believe that the primate biosatellite programme should continue in parallel with the manned space programme.

Major engineering decisions determining the character of possible future space stations, logistic systems, and advanced spacecraft are dependent on the valuation of man's potential for useful work in space. We are faced with the question of qualifying man for more complex tasks in space for longer flights and of evaluating man as an integral part of the spacecraft man-machine system, and we face this question without sound biomedical foundations. What is meant by the phrase to 'qualify' man: the determination of man's ability to survive in space over extended periods and continue to perform effectively; to maintain satisfactory interpersonal relationships with crew members; not be adversely affected by his return to earth and maintain his total well-being during his period in space? But a much broader meaning to the term to 'qualify man' implies a detailed knowledge of the unique capabilities and capacity of the human organism, of the optimal contributions of this organism to the performance of space flight with a wide variety of objectives, and development of a predictive ability for performance or response based upon preflight information. The ultimate qualification of man is the achievement of a depth of understanding about his role in space that will permit his optimal integration into future space programmes.