Animal Studies of the Subgravity State during Rocket Flight

By J. P. Henry, M.D., Captain E. R. Ballinger, USAF (MC), Major P. J. Maher, USAF, and Major D. G. Simons, USAF (MC)

Aero Medical Laboratory, Wright Air Development Center
Wright-Patterson Air Force Base, Ohio

IN THEIR DISCUSSION of man under gravity free conditions, Gauer and Haber[6] were the first to suggest that subgravity might lead to interesting physiological effects. They did not anticipate direct disturbances of respiration and of the circulation. However, they thought that the conflict between normal visual observations and the changed impulses from the labyrinth and proprioceptive apparatus might eventually lead to disturbances in performance and even to motion sickness. At the time they proposed this, no practical means for producing the weightless state was available. Subsequently, Haber and Haber[7] pointed out that this condition could be briefly reproduced by an aircraft or rocket which followed a ballistic trajectory. If the vehicle follows a course in which the horizontal velocity is constant and a downward acceleration exactly equaling the earth's gravity is developed, then no support is provided to objects within it and they become essentially weightless. Throughout the period that a high altitude research rocket coasts to its 200,000 to 400,000 foot apogee during free ascent following burnout, it is decelerating at 1 g because atmospheric resistance is negligible. Thus, until it again encounters atmospheric friction in the downward leg of its parabolic flight such a missile effectively provides a gravity free environment.

Because mechanical support by the atmosphere is grossly deficient in regions in which pilots of contemporary rocket aircraft are already flying, subgravity and zero gravity states of brief duration are already occurring and they will occur with increasing frequency as flight altitudes are extended.[8] The need for information as to the various physiological reactions which might be expected during such brief episodes has been stressed by several investigators.[1] Therefore, when the opportunity arose to make some studies in the V_2 and Aerobee rockets used for upper atmosphere research, it was welcomed. This report summarizes the preliminary results obtained during the first four years of work.

METHODS

Five V_2's and three Aerobee sounding rockets were used. The V_2's were heavily loaded with various experiments for study of the physical conditions existing by day and night in

Presented at the Twenty-third Annual Meeting of the Aero Medical Association, Washington, D. C., March 17-19, 1952.

This paper should be read in conjunction with those appearing in the Space Medicine Section in the August issue. Unfortunately, it was received too late to include with the other papers.

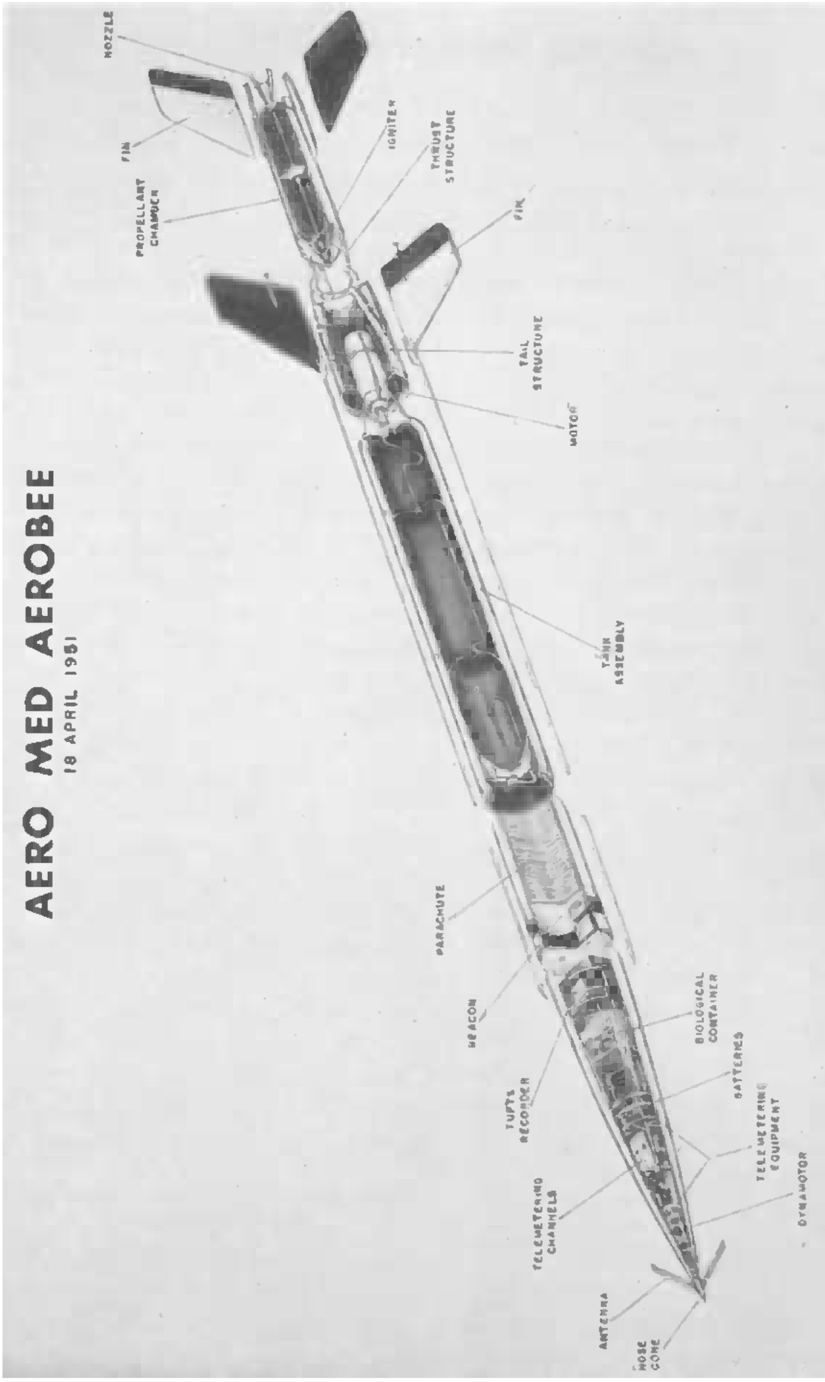


Fig. 1

Expanded diagram of an Aero Jet Aerobee Sounding Rocket showing pressurized nose cone with parachute. The nose cone is divided into a forward section carrying the telemetering equipment and a rear section in which the anaesthetized monkey and rotating mouse drum are placed together with a camera, oxygen supply and sodalime canister.

the ionosphere. However, space was allocated to accommodate a capsule approximately three feet in length and fifteen inches in diameter which lay transverse to the long axis of the missile in the instrumented nose section. Only the second and third Aerobees were instrumented specifically for physiological studies. In them, the entire nose section was taken up with biological recording and telemetering equipment (See Fig. 1). The nose sections were all equipped with parachutes and it was hoped to recover both instruments and specimens. In the V_2's and Aerobee I technical difficulties intervened and there were no successful parachute recoveries. Nevtheless, in most cases satisfactory data were obtained up to the moment of impact either by telemetering of the physiological variables under study or, in the case of a photographic record, by using a strong steel casette which survived the impact forces. Aerobee II was recovered intact and the instrumentation from this missile was flown again with minor modifications in Aerobee III when it was again successfully parachuted without damage to animals or equipment.

Two types of study were conducted:

1. In the first, physiological observations were made either of pulse and respiratory rhythm, or of arterial and central venous pressures. These data were obtained on seven anaesthetized Rhesus, Cebus or Cynomolgos monkeys. Anesthesia was restricted to intravenous sodium pentabarbital to cover the period during which electrodes or cannulae were inserted. It was followed by intravenous and/or subcutaneous morphine in the sedating dosage of 2 mg./kg. The animals were securely immobilized in the extended posture on sponge rubber beds by nylon netting. In all the V_2's and in one Aerobee, impact due to parachute failure was of the order of several thousand g's and death was instantaneous. In the case of Aerobees II and III, satisfactory parachute deployment resulted in the recovery of live animals. However, in Aerobee II, there was some delay in extremely hot environmental conditions before return to the base could be effected and the apparently uninjured monkey died en route although the mice survived. Since autopsy was negative, it was presumed that death was due to heat prostration. In the case of Aerobee III, the capsule was located almost immediately and the two unharmed animals were returned to the laboratory within an hour after the firing.

The capsules were provided with an eight-hour supply of oxygen in a high pressure cylinder and a fan recirculated this through a sodalime canister to absorb carbon dioxide and water vapor. Respiration was recorded by a thermocouple in the orifice of a special rubber face mask. Electrocardiograms were picked up by subcutaneous needle electrodes in the leg and chest. In Aerobees II and III the venous and arterial cannulae of polyethylene tubing of 0.23 mm. ID were connected to Statham pressure transducers of appropriate ranges.[11] In order to prevent clotting, the cannulae were continuously fed by two automatic syringes at 4 cc./hr. with physiological saline containing Sodium Heparin. Following conversion into electrical impulses, the physiological variables were amplified and applied to a frequency modulating subcarrier oscillator and then fed into an FM transmitter in the V_2 or Aerobee nose section. The signal from this was received over distances of more than 80 miles by the ground stations of the Holloman Air Development Center and White Sands Proving Ground, rocket range. There they were converted into the familiar physiological wave forms and recorded on photographic paper by oscillographs.

2. In the second type of study, observations of performance were made on five mice by direct photography. In one case a small capsule was placed in a V_2 and the behavior of a single mouse was photographed for one-second periods at four-second intervals throughout the flight. In the later studies in Aerobees II and III a cylindrical drum 6 inches in diameter rotating about an axis transverse to the long axis of the rocket was employed to study and contrast the behavior of two mice when they were exposed to subgravity. The drums were divided into two 2½ inch wide smooth surfaced compartments. An electric motor drove the drum in Aerobee II at 12 rpm and that in Aerobee III at 4 rpm.

In the Aerobee II test each compartment contained a small paddle over which the mice had to climb and the behavior of a normal animal was contrasted with that of one which had previously had an electro-cautery needle applied to the horizontal semicircular canals in the membranous labyrinth,[10] while under ether anaesthesia. This animal showed marked signs of labyrinthine disturbance including a characteristic inability to keep its orientation when submitted to the test of swimming in a water bath. Control histological sections of such operated animals showed degeneration of the sensitive regions in the labyrinth.*

In the V_2 experiment the single mouse was presented a firm foothold on the wire gauze floor of a fixed cage. This permitted reliance on his tactile and visual sense during the period of subgravity. In the drum experiment in Aerobee II the aim was to differentiate between the behavior of a normal and a labryinthectomized mouse when both were deprived of adequate tactile and visual orienting stimuli by the rotation of the smooth walled drum. It was also possible to observe the time taken for the mice to resume normal activity following the "return of gravity" when the parachute slowed the missile to a constant velocity and the mice regained their normal "weight." A record of the activity of the mice in the drum during the two to three minute subgravity period, and for two to three minutes subsequently during the parachute descent was made on sixteen millimeter film taken at 14 frames/sec. In the experiment in Aerobee III only one of the compartments was provided with a paddle. The edge of this was designed with a projection so that the animal could easily cling to it if he so desired. In the other compartment care was taken to provide no point where the animal could get a grip and hold on. This experiment was aimed at differentiating

*These preparations were skillfully made by Lt. J. C. Richert to whom the authors wish to express their appreciation.

TABLE I.

	Pulse Rate Per Minute				Respiration Per Minute			
	Control	Powered Ascent	Subgravity	Free Fall	Control	Powered Ascent	Subgravity	Free Fall
Approx. time in seconds		0-50	50-200	200-400		0-50	50-200	200-400
Acceleration	1 g	4-6 g	0.1 g	1 g	1 g	4-6 g	0.1 g	1 g
Expt. No. V_2a	190	110	190-180	—	90	60	65-60	—
V_2b	190	200	210-200	200	40	50	60-50	
Aerobee I	210	220	190-185	220	60	65	60-20	60
Aerobee II	166	172	178-178	175				
Mean	190	175	190-185	205	60	60	60-40	60

Pulse and respiratory rates of narcotized monkeys during a control period, powered ascent, exposure to subgravity and subsequent free fall or parachute spoiled descent; showing the absence of any gross disturbance during the period of zero gravity.

between the behavior of a normal animal provided with a firm foothold and that of one to whom both tactile and visual points of reference had been denied.

RESULTS

Pulse and Respiration. Table I is a composite of all the pulse and respiratory rate measurements made in the first four successful flights. Although the duration of powered ascent and subgravity varied for different flights, the time is expressed in approximate averages giving two and one-half minutes as the mean value for the duration of subgravity.

The pulse rates of the small animals used in this work were normally very high and the 190/min. mean for the control period before takeoff is within physiological limits. The subsequent changes in pulse rates are probably not significant. This also holds for the respiratory rates, for although there was a suggestion of breath-holding immediately following the abrupt change from powered ascent to the weightless condition, this was not consistent and in general there was no change in respiratory rhythm throughout the flight.

In Aerobee III two small monkeys were used, one of which was placed in the upright seated posture so that the accelerations induced by the rocket motor acted in the direction seat to head. The other lay supine with the long axis of the body transverse to that of the missile. Pulse rates were obtained in both these cases as well as in the four animals mentioned above. There was no significant change in the pulse rate of either animal throughout the flight.

The initial acceleration experienced in the flight was the thrust of the rocket motor. In the case of the V_2 this ranged from 4 to 5 g. Calculations based on analysis of telescopic camera observation of the behavior of these rockets suggested that the residual accelerations experienced by the specimens during the period of free ascent approximated the true zero gravity condition very closely. This is because this missile is very stable and does not rotate rapidly about its long axis. In the Aerobee there was a brief two and one-half second initial 15 g "kick" from the solid propellant booster (Fig. 1) following which the aniline nitric acid rocket motor gave steady forty-five second thrust with a maximum acceleration of 3 to 4 g. Following the sudden cutoff of power

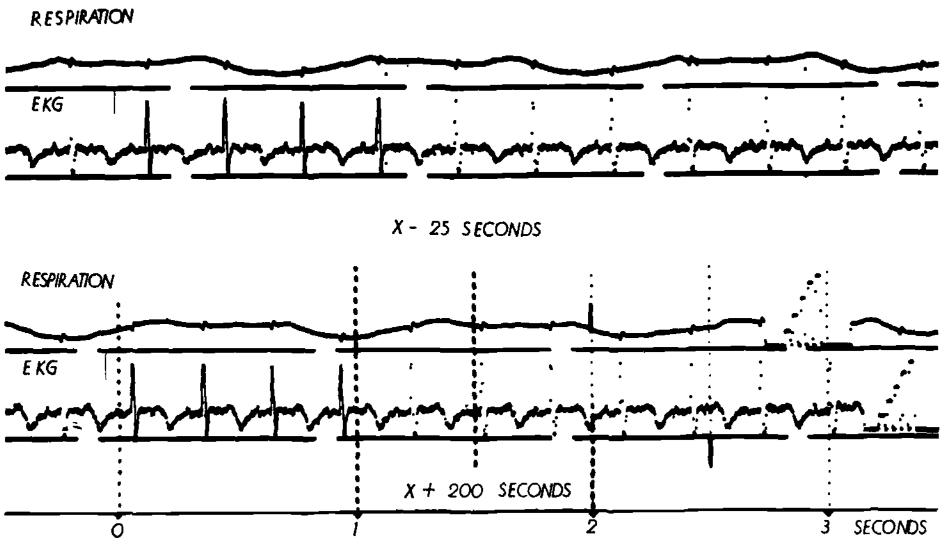


Fig. 2.
Respiration and electrocardiogram of an anesthetized monkey in a capsule in a V_2 as recorded by the ground station. Above, 25 seconds before takeoff. Below, at zenith after 140 seconds of subgravity and at 80 miles altitude. There is no significant change in respiratory pattern and the electrocardiogram has not changed appreciably. The latter is a modified chest lead with a normally inverted T wave.

at burnout, which occurred in Aerobee III at approximately forty-five seconds at 65,000 feet and a velocity of 3,000 feet per second, the period of free ascent commenced. In this type of rocket the conditions for attaining the "weightless" state were not so favorable because the vehicle has a natural roll rate during free flight of approximatly 1 per second. This motion, combined with some pitching and yawing, gave rise to transverse accelerations of the order of 1/20 g. Accelerometers placed in the three axes of the rocket confirmed that the subgravity state was less in all directions than the 1/10 g limit of their sensitivity. However, in Aerobee III a small rubber pellet placed in one compartment of the drum clearly demonstrated that the axial rotation of the rocket was creating a residual acceleration of the order of 1/20 g transverse to the long axis. This rotation was modified at separation of the nose cone since the pellet no longer stayed in one spot in the drum but drifted from side to side.

Electrocardiogram. The upper record of Figure 2 was taken twenty-five seconds before the takeoff of one of the V_2's. The chest and leg leads and recording system employed, gave an inverted T-wave in the normal resting state. At zenith, an altitude of 80 miles, and 225 seconds after takeoff, neither the form of the respiratory wave nor the electrocardiogram had undergone any significant alteration. The clear tracing free from muscle action potentials was evidence of the satisfactory narcosis which was deep enough to provide good relaxation and clear records throughout the flight.

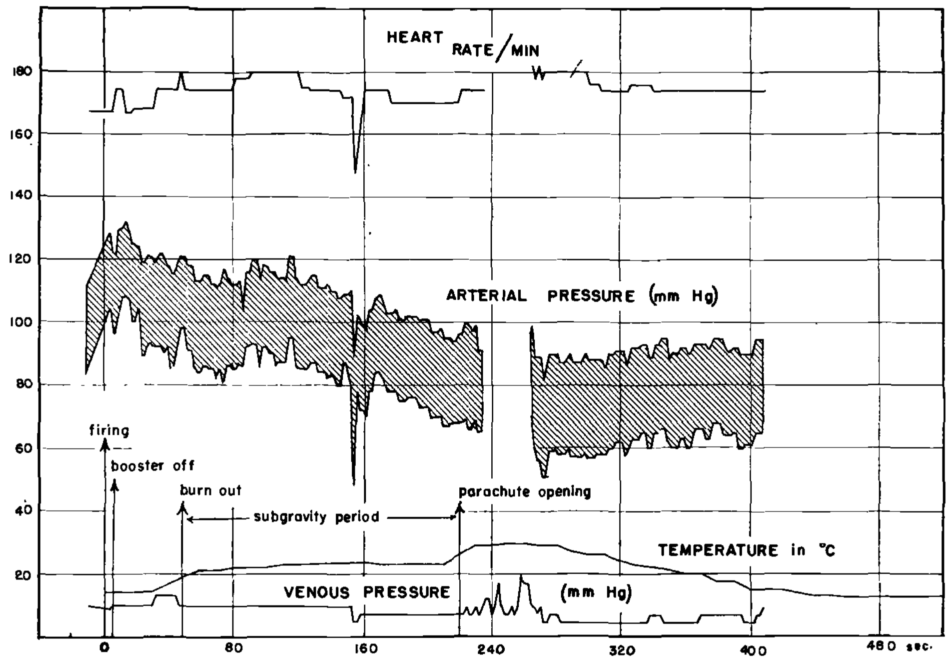


Fig. 3.

Chart showing behavior of heart rate, blood pressure, capsule temperature and central venous pressure during the flight of Aero Medical Aerobee II to a 40 mile apogee, with successful parachute descent of the nose capsule. Abscissa time in seconds; ordinate in units given in legends over respective graphs.

Arterial and Venous Pressure: In Aerobee II, the single case in which this measurement was successfully obtained, the control arterial pressure of 113/80 mm. Hg was well within normal limits (Fig. 3). There was a slight rise to 130/100 mm. Hg which was associated with the firing of the booster and the initial phases of ascent out of the launching tower. Then the arterial pressure steadily and relatively uneventfully subsided until the moment of parachute opening when the record was lost for twenty to thirty seconds. The gradual decrease during the subgravity phase was followed by the opposite behavior during the steady descent on the parachute at slightly more than 1 g. During the initial phases of this latter period both diastolic and systolic pressures rose by approximately 10 mm. Hg. For the last 200 seconds of parachute descent until impact at 600 seconds, the arterial pressure remained constant.

The changes in venous pressure recorded in Aerobee II during take-off and subgravity do not appear to be significant. There are no sharp rises that would be associated with breath-holding and struggling. However, there is a short series of minor increases from 10 cm. H_2O to a maximum of 27 cm. H_2O during the parachute opening phase which may have been associated with brief breath-holding episodes; thereafter the pressure remains constant at 6.5 cm. H_2O.

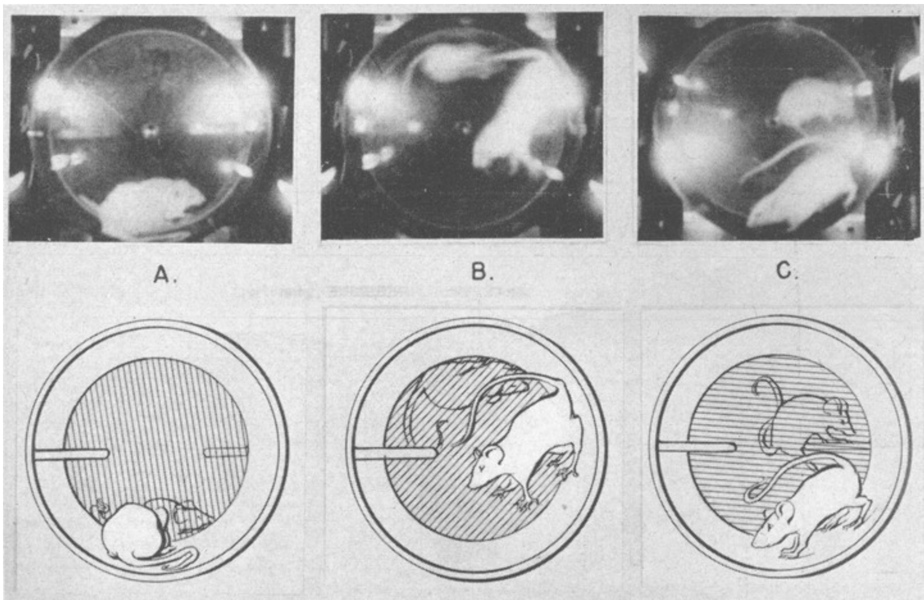


Fig. 4.

Single scenes from a motion picture of two mice in a two section rotating drum in Aerobee II. (Below each photograph is a line diagram to bring out detail.)

A. Mice at rest in their compartments before takeoff.

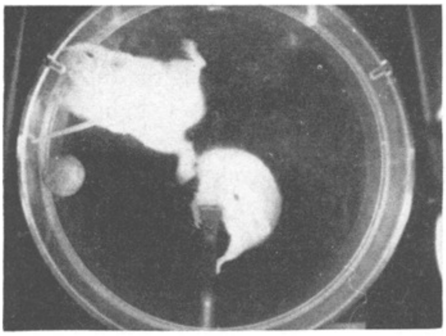
B. Subgravity 120 seconds after takeoff at 40 miles altitude. The normal mouse is "floating." The other clings to an irregularity in the drum.

C. One second after parachute opening the normal mouse has immediately recommenced normal running action while the labyrinth damaged animal climbs onto the paddle.

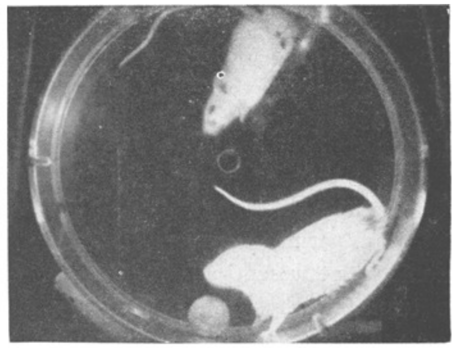
Mouse Performance. The above measurements of the cardiovascular responses show that, as Gauer and Haber[6] had predicted, there are no gross, immediate and direct cardiovascular disturbances as a result of two to three minute exposures to subgravity one-twentieth the normal stress. However, this was no assurance that a normal unanaesthetized animal with undulled reflexes and sense organs would not be seriously incapacitated by subgravity. However, in another type of experiment, the smallest mammal obtainable was placed in a nonrestraining environment and photographed to observe the effect of subgravity on its behavior.

The first of these tests was carried out in a V_2 using a mouse in a cage whose wire gauze floor gave him a firm foothold. The animal was disoriented but retained normal muscular coordination following the onset of the weightless condition. It was clear that he no longer had a preference for any particular direction, and was as much at ease when inverted as when upright relative to the control starting position. For the most part he clung quietly to the wall and when he moved, did so with normal dexterity.

The results of the next mouse experiment in Aerobee II in which the rotating drum was employed with a normal and labyrinth damaged mouse are summarized in Figure 4. In Figure 4A, the two mice exhibit a normal crouching posture prior to take-off; 4B was taken during subgravity. The labyrinth damaged animal clings quietly to a slight projection in his compartment and rides around with the drum. The normal mouse is characteristically suspended in mid-air with claws extended in the attempt to find a secure foothold. His actions betray disorientation but no lack of coordination. Figure 4C was taken one second after parachute opening and the onset of 1 g. It shows the labyrinth damaged animal scrambling onto his paddle, while the normal mouse has resumed running and is preparing to jump with his normal dexterity and coordination immediately after two and one-half minutes of the subgravity state. This activity continued up to the moment of landing on the sands ten minutes after firing, uninjured. The final experiment at which time the mouse was recovered in Aerobee III confirmed the observation made earlier in the V_2 that, if given the opportunity to use his tactile sense and cling to something, an animal will remain oriented and quiet. Figure 5A shows how the one mouse holds firmly to the paddle while the other normal



A



B

Fig. 5.

Single scenes from a motion picture of two mice in a two section rotating drum in Aerobee III.

A. Photograph of mouse drum shortly after separation and two minutes of subgravity. The rubber indicator pellet in the smooth front compartment is floating out of contact with the wall. The mouse is "suspended" in a characteristically disoriented posture. The mouse in the rear compartment clings to the projections on the paddle and retains his orientation.

B. Taken a few seconds after parachute opening when the deceleration applied to the nose cone by the drag chute approximates 1 g. The mouse in the front compartment is standing poised and normally oriented as he follows the drum movement. In contrast with 5A the rubber ball is now supported by the drum. The mouse in the rear compartment prepares to jump off the paddle with normal agility.

animal, unable to grasp anything, moves violently from side to side of the compartment in the attempt to find similar security. Figure 5B shows their normal behavior within a few seconds after parachute opening at a time when the deceleration induced by its drag is providing an orienting force of approximately 1 g inside the drum.

DISCUSSION

The experiment using anaesthetized monkeys represents the first attempt to transmit physiological information from a rocket by telemetering techniques and as such the quality of the data obtained is a tribute to the technical accomplishment of the responsible engineers.[9]

The tables of pulse and respiration data and the electrocardiograms in the case of these relatively lightly anaesthetized animals showed a remarkable freedom from evidences of disturbance. This undisturbed functioning of the cardiovascular system fully upheld the predictions that the stresses of powered ascent, of a relatively prolonged subgravity state, and of free fall, often with a violent, tumbling, spinning motion, would not significantly disturb a properly secured animal. As such, the data is good evidence that capsule escape from vehicles traveling far into the ionosphere is feasible, providing successful spoiling systems can be developed to "brake" the descent.

The 15° Centigrade rise of internal temperature within the nose of Aerobee II in the four minutes between take-off and zenith is evidence of the strong heating effect as the rocket attained a speed of approximately one mile per second in the upper atmosphere. While a considerable portion of this heating effect arose from skin friction, a portion of it may be the direct result of thermal solar radiation at very high altitudes.

The slow fall in systolic and diastolic arterial pressures during the subgravity phase of the Aerobee II flight may be significant. It may represent a reaction of the cardiovascular system to the subgravity condition in which hydrostatic pressures are virtually eliminated. The slight upward trend of the blood pressure following parachute opening and the return to 1 g supports this suggestion. Further evidence on this point would be desirable, especially in view of the temperature changes in the capsule which might also have played a part in causing blood pressure fluctuations.

The mice were exposed to the subgravity condition in differing circumstances. Both the animal in the V_2 and one of those in Aerobee III were able to rely on their tactile and visual senses for orientation as they clung to the walls of the cage or to the paddle. Their state would correspond to that of a pilot firmly strapped into his seat with a conventional harness. As was to be expected, they betrayed little disorientation and no loss of coordination. They merely lost the vertical reference of gravity and assumed whatever posture was convenient.

The operated animal in the second experiment showed the classical symptoms of bilateral labyrinthine loss. However, by using visual and tactile senses, he was able to perform with reasonable dexterity at 1 g in the rotating drum. It had been predicted that exposure to a subgravity state would be less likely to disturb this animal than the normal one. The latter would experience a sudden deprivation of labyrinthine information to whose absence the operated animal had already become adapted. The sudden gross decrease in orienting stimuli might give rise to a sensation of "falling" and lead to confusion and a failure to use what tactile stimuli he could obtain from the smooth rotating drum. The operated animal would presumably experience no such "withdrawal symptoms." It was probably not pure coincidence that the operated animal found a foothold and quietly rode around with the drum during the subgravity state while the normal animal neglected his paddle and made disoriented escaping efforts throughout this phase of the flight.

The behavior of the mouse in the Aerobee III compartment without a paddle was the same as that of the normal mouse in Aerobee II with a paddle. Although there was an orienting force of approximately 1/20 g which remained relatively steady for most of the subgravity period, there were times, as for instance during the twenty to thirty seconds following separation and preceding opening of the drag parachute, when the gravitational force as indicated by the ball within the compartment fell to zero. At other times it changed direction repeatedly. The animal's violent movements may have been due to the fact that the reduction of his apparent weight to less than 5 per cent of its normal value resulted in a gross disproportion between the effort required for a movement and that actually expended in pushing against the drum wall. More prolonged periods of subgravity might answer this point and show whether the animal would learn to expend less force in making necessary movements in the compartment.

Whatever may be the explanation of the difference in behavior between each of the animals during these two subgravity state experiments, the immediate resumption of normal activity by all of them, with the return of the normal pull of gravity, implies that quite prolonged and marked reductions in this force produce no lasting disorientation or incapacitation in a mouse.

Physiological results obtained with monkeys and mice can only be applied to men with caution. Fortunately, during the past year, two independent reports of pilot performance during states of subgravity and near zero gravity have become available. Crossfield[5] has found no significant difficulty in performing all actions necessary to control an aircraft during an often repeated exposure to near zero gravity states of the order of half a minute. Elsewhere, Ballinger[2] has presented his own similar observations of unimpaired human performance during brief exposure to the subgravity state.

It may be concluded that, while much remains to be done in this new area, and refined experiments are needed to determine the exact nature of the minor difficulties reported, the weightless state, as it is likely to be encountered for brief one to two minute periods in contemporary rocket and jet aircraft, will not seriously interfere with proper performance of a pilot's duties. Meanwhile, investigation of the original question raised by Gauer and Haber[6] of the effects of prolonged weightlessness lasting for hours or days awaits the development of the orbital rocket.[3,4]

SUMMARY

1. Pulse, respiration, electrocardiogram and arterial and venous pressures have each been telemetered from one or more of seven anaesthetized primates in four V_2 and three Aerobee rockets during subgravity periods lasting for two to three minutes. There was no evidence of a significant disturbance of the cardiovascular or respiratory systems.

2. Photographic records of the performance of five mice have been made through two to three minute periods of subgravity. As long as a foothold was available to the animals they did not appear seriously disturbed. In all cases the animals ran and jumped normally immediately following resumption of an orienting gravity stress.

3. The weight of evidence suggests that in currently attainable durations of two to three minutes the subgravity state will not lead to any serious psychophysiological difficulties.

4. Investigation of the effects of subgravity states lasting for hours or days must await the development of orbital rockets.

ACKNOWLEDGMENTS

The major problems in this work were ones of engineering and instrumentation. The authors wish to express their appreciation for the skill and craftsmanship of M. A. McLennan, E. G. Correll, E. Gienapp, H. E. Childers and the others who made the biological phases of the work possible. The early studies in V_2's were successful only because of the generous cooperation and consideration of Dr. Marcus O'Day and the staff of the Air Force Cambridge Research Center.

REFERENCES

1. Armstrong, H.; Haber, H., and Strughold, H.: Aero medical-problems of space travel. J. Aviation Med., 20:383, 1949.
2. Ballinger, E. R.: Human experiments in subgravity and prolonged acceleration. J. Aviation Med., 23: 319, 1952.
3. Clarke, A. C.: Interplanetary Flight, An Introduction to Astronautics. Temple Press, London E.C.I., 1950.
4. Coggins, J., and Pratt, F.: Rockets, Jets, Guided Missiles and Space Ships. New York: Random House, 1951.
5. Crossfield, A. B.: Personal Communication.
6. Gauer, O., and Haber, H.: Man under gravity-free conditions. Chapter VI, German Aviation Medicine, World War II, Volume I, U. S. Air Force Publication, Supt. Documents, 1950.
7. Haber, F., and Haber, H.: Possible methods of producing the gravity-free state for medical research, J. Aviation Med., 21:395, 1950.
8. Haber, H., and Gerathewohl, S. J.: Physics and psychophysics of weightlessness. J. Aviation Med., 22:180, 1951.
9. McLennan, M. A.; Correll, E. G., and Childers, H. E.: The Telemetering of Physiological Data. USAF Technical Report—in preparation.
10. Shall, T. A., and Rambo, J. H.: Electrocoagulation of the membranous labyrinth. Ann. Otol. Rhin. & Laryng., 57: 590, 1948.
11. Statham Laboratories, Beverly Hills, California. P23 Type Pressure Transmitter, Bulletin No. 313.