PROSPECTS AND LIMITATIONS OF HUMAN FLIGHT BEYOND THE ATMOSPHERE

The Elusive Spheres of Interest

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The prospect of manned flight into space is imminent. This fact has been emphasized by the series of successful flights of American and Soviet satellites within the past year. The U.S. capability of lifting large manned satellites is apparent from the announcements emanating from certain United States military agencies. Specifically, the United States Air Force, with its announced development of rocket boosters with intercontinental ranges, will at some future date be capable of placing a human operator into orbital flight. Preceding this event a series of analyses of human capability for performance in a space vehicle has been developed. To a large extent all known parameters of extra atmospheric space flight, with the exception of weightlessness and cosmic radiation, may be closely simulated under terrestrial conditions. Man's tolerance for heat loading, accelerative stresses, work cycling, and limits of physiological performance have been generally delineated. However, a great data hiatus and, to some extent, controversy, exists with respect to two elusive spheres of interest: exposure of tissues to primary cosmic particles and to a zero *g* field. Experience in these nether regions of space medicine has been limited to mere brief glimpses at the problems, and it is with these two spheres of concern that I wish to deal today.

I. WEIGHTLESSNESS

We have been teased for many years by *brief exposures* and fleeting glimpses of near zero *g* environments. Human experiments have been limited to aircraft flights yielding less than one minute of weightlessness. Animal experimentation in the U.S. and U.S.S.R. has been limited to a prolonged ballistic (satelloid) trajectories culminating in the satellite flight of Sputnik II with a canine subject. In general, none of these experiments, with animals or human subjects, has given us serious concern for the mental or physical health of the space pilot living for periods of minutes to a few hours in the "appressionless" state.

Of utmost importance will be operant performance data viewed from work decrement and physiological viewpoints. However, much valuable basic scientific data has yet to be gained from lower animal studies.

Human subject experiments have included studies of general psychological response, mechanical problems of nourishment and deglutition, attempts at micturition, and others. The problem of elimination of liquid body wastes at zero *g* was recently studied in some detail with the "brief exposure" technique. Thus far there is indication of no insurmountable human factors problem if consideration is given to adequate crew screening, selection and training, accompanied by a "weightless engineering" concept applied to the environment and life support systems of the space cabin capsule. This is obviously most important for mechanical hydraulic systems, including hydraulic physiological mechanisms.

Method

Therefore, a study[(1)] was begun to ascertain whether elimination of urine by human subjects could be accomplished during 30–40 sec of weightlessness produced by an F–94C STARFIRE jet aircraft. The technique for producing weightlessness has been described elsewhere[(2)]. Male volunteers were utilized ranging in age from 18 to 42 years. All were highly motivated to succeed. These volunteers were chosen from civilian, airmen and officers of the staff of the School of Aviation Medicine. Four had no previous flying experience in jets, four had one to two hours, seven had between two and ten hours, seven had between ten and one hundred and two individuals had over one hundred hours of jet time. No information concerning the success or failure of other subjects was given on the first flight.

The subjects were requested to drink a glass of water every fifteen minutes for two hours prior to flight time. In almost every case, this assured the presence of a distended urinary bladder at the time of the experiment; most subjects expressed complaints of relatively severe discomfort. Several individuals were forced to urinate prior to take-off or during the take-off roll but had partially or completely refilled their bladders prior to attaining maneuvering altitude and burning out the jet tip-tanks.

The ordinary cockpit relief tube is completely unacceptable for use in weightlessness because of inability to direct the flow of urine into the tube orifice. Therefore, a simple urinal was devised from weather balloon and scrap oxygen tubing. This was unsatisfactory when the flow of the urinary stream was reduced because there was then insufficient pressure to force the liquid column in the oxygen hose down into the balloon.

The subjects were instructed to be prepared to initiate micturition prior to entering the parabolic maneuver by loosening clothing, lap belt and parachute harness but the actual initiation of urination was not to be attempted until the pilot and the subject were satisfied that weightlessness had been achieved. Each subject was exposed to at least two parabolas for this purpose of each flight.

When a subject was unable to micturate during the brief exposure to weightlessness he was given an opportunity to empty his bladder during a similar specified time period while in straight and level flight. Three such attempts under 1g were allowed per flight.

Results

The basic results are presented in Table 1. Twenty-six subjects participated in one or more micturition-subgravity flights. A total of thirty-seven

TABLE 1

Micturition in the Weightless State

Subject No.	No. of flights	Hours jet time	Micturition at zero g	Micturition in level flight	Greatest degree of urgency loss reported	Vomiting
1	1	10	Mission abortion	—	—	Yes
2	2	10	Yes	—	3	Yes
3	4	32	Yes	Yes	3	No
4	2	16	Yes	—	0	No
5	2	6	Yes	—	2	No
6	2	30	Yes	—	3	No
7	1	50	No	No	2	No
8	2	1	Yes	Yes	3	No
9	1	7	Yes	Yes	3	No
10	1	1800	Yes	Yes	3	No
11	1	100	Yes	Yes	0	No
12	1	30	Yes	Yes	2	Yes
13	1	2	Yes	Yes	0	No
14	1	10	Yes	Yes	1	No
15	2	20	Yes	Yes	3	No
16	1	10	Mission abortion	—	—	Yes
17	1	1	No	Yes	0	No
18	1	0	No	No	0	No
19	1	2	No	No	3	No
20	1	0	Yes	Yes	0	No
21	1	30	Yes	—	0	No
22	1	20	Yes	—	0	No
23	1	1	No	No	0	Yes
24	1	0	Yes	—	0	No
25	2	0	Yes	—	3	Yes
26	2	3	Yes	—	3	No

flights were made during which nineteen subjects were able to initiate micturition. Four of these able to perform micturition were able, with great effort, to force only small quantities of urine from their bladders. Two subjects became so ill early in the flight that their marked nausea and vomiting caused mission abortion before any observations concerning micturition could be made. Of those five individuals unable to urinate during zero *g*, four were unable to urinate into the cockpit relief tube during straight and level flight. This group of five subjects included one individual with no previous jet experience, three individuals who had flown one to two hours and only one individual (a pilot) with slightly over fifty hours of jet time.

Ten subjects reported a marked decrease in urinary urgency during one or more of these brief exposures to weightlessness. Four subjects noted slight to moderate loss of the sensation of urgency; however, ten subjects were unable to detect any change. In each of the former fourteen cases, return of urgency paralleled the return of the *g* field. Several subjects became ill and vomited when they strained hard with tensed abdominal musculature, and it is believed that these may represent examples of the mechanical "weightless regurgitation phenomenon"(3). However, several other subjects became nauseated after beginning micturition or after emptying their bladders; these probably reflect the effect of a "vagal shower" phenomenon commonly observed by urologists. Four subjects reported that once micturition had been initiated in zero *g* they were unable to detect the usual pressure clues indicating urination was continuing without visual reference.

Discussion

Although no firm conclusions concerning men's response to weightlessness should be drawn from experiments utilizing the *brief exposure* technique, perhaps a few inferences can be made. It would appear that opening of urinary sphincters and initiation of micturition can be accomplished with little or no difficulty. It seems probable that the vesicular trigone is the primary sensory zone for perception of bladder fullness, rather than the stretch receptors located within the wall of the urinary bladder. Perhaps the most obvious factor underlying the variability in subject awareness of urinary urgency in this experiment was the lack of a perfect zero *g* field (actually a varying subgravity field) and the presence of relatively high accelerations (3 *g*) before and after each parabola. This "impurity" of zero *g* exposure is most undesirable but equally unavoidable at this time. In addition, the fear and apprehension associated with the first few hours of exposure to the jet cockpit environment tends to divert attention. Only four of the subjects reporting no change in sensation of urgency had more than two hours of jet flying time before the experiment. The partially or markedly diminished sense of urgency during weightlessness may constitute a potential problem for long-range space flights, however, elimination of body wastes can be accomplished on a firm schedule.

Summary of Micturition Data

1. Twenty-six subjects were exposed to a total of thirty-seven separate jet aircraft flights during which zero *g* parabolic flight maneuvers were performed. Attempts to initiate micturition during weightlessness following a period of hydration were studied.
2. Only one subject was unable to void at zero *g* but was able to urinate in straight and level flight. Four subjects were unsuccessful in either situation. With one exception, all five of these subjects had two hours or less of jet flying experience.
3. A majority (58%) of the subjects noted a slight to marked decrease in urinary urgency when exposed to weightlessness. It therefore, appears that the floor of the bladder may be the primary sensory zone for the sensation of bladder fullness.
4. Scheduling of body-waste elimination should be incorporated into the space-crewman's standard operating procedures and check list.
5. Special consideration must be given to the design and development of a satisfactory urine receptacle.

II. COSMIC RADIATION

Using nuclear track plates, much information has been obtained about primary cosmic rays. High-altitude balloon and rocket flight has shown that incoming cosmic radiation consists of highly-energized nuclear particles. Each nucleus is entirely ionized, i.e. it has no orbital electrons, and carries a maximum positive charge. Cosmic radiation consists of nuclei of the elements from hydrogen through iron, but rarely beyond. Hydrogen and helium nuclei comprise approximately 96% of the total charge spectrum, and the remaining 4% is comprised of nuclei of the medium and heavy elements.

All primary cosmic ray nuclei have been accelerated to velocities approaching the speed of light. Most of them arrive at the earth's atmosphere with speed corresponding to a minimum cutoff energy or an acceleration of one billion electron volts per nucleon. In general, nuclei of progressively higher energy are observed in decreasing abundance. The minimum energy heavy nuclei (carbon through iron) are of greatest biological interest.

Low-energy primary cosmic ray particles hurtle through space in the vicinity of the earth's orbit. As they approach near the earth, they are absorbed by the earth's atmosphere. Many are first deflected from equatorial regions by the earth's magnetic field due to the charged condition of each primary nucleus. Within 1000 miles of the earth there is nearly complete shielding from low-energy primaries through the first 50° of geomagnetic latitude. Medium- and high-energy particles penetrate the magnetic field to the atmosphere, and most are converted to secondary cosmic radiation. Poleward of 55° geomagnetic latitude there is essentially no magnetic protection from primaries.

Once within the atmosphere many low-energy particles are stopped above 80,000 ft and their energy expended in ionization of the air through which they pass. This event is termed a "thin-down" because of the tapered appearance of the track in nuclear emulsions. The remaining low-energy particles and essentially all high-energy ones eventually collide with atomic nuclei of the traversed material. Each collision results in mutual disintegration and is called a star because of its stellate appearance in nuclear emulsions. The collision of heavier primary particles occurs in the 80,000–100,000 ft region. Secondary cosmic radiation is the resultant energetic nuclear debris of neutrons, protons, mesons, etc. For biological considerations, only secondary radiation occurs below 75,000 ft and is responsible for the total ionization of air by cosmic rays reaching a maximum value in the 75,000 ft region.

Therefore, the low-energy heavy primaries are of greatest interest since they often terminate as thin-downs, whereas high-energy particles usually terminate as stars. In equatorial regions positively-charged nuclei are deflected crossing the lines of the earth's magnetic field. The low-energy particles enter the atmosphere at high latitudes (polar regions) where they come in parallel to the magnetic line of force. Along the northern border of the central United States, exposure to the full spectrum of cosmic ray primaries can be achieved. Animals flown from Holloman Air Force Base, New Mexico, have served as controls since they are subjected to identical flight conditions including cosmic ray secondaries, but essentially to no heavy-primary pre-thin-down hits.

The geomagnetic protection effect is especially significant in terms of satellite flight since equatorial orbits of less than approximately 45° geomagnetic latitude remain within the "zone of protection" produced by the magnetic shielding effect of the earth's magnetic field. Exposure to cosmic ray primaries in such orbits at less than 1000 miles apogee will be comparable to the control balloon flights from New Mexico. Not until flights of many earth's radii are conducted will full, continuous exposure to cosmic ray radiation be experienced, since even polar orbits spend part of their time passing through the equatorial zone of protection.

Two series of balloon flights to investigate the biological hazard inherent in primary cosmic radiation were launched from the northern border of the United States in 1954 and 1955. The 1954 flights exposed animals to a maximum number of thin-downs in the 90,000–95,000 ft region. On the 1955 flights, animals were exposed between 117,000–122,000 ft for maximum exposure to thin-downs by the heaviest commonly-observed cosmic ray primaries (near the weight of iron).

Two different types of experiments were conducted, i.e. the assessment of the indirect biological effects of cosmic ray primaries from damage caused by one or more pre-thin-down hits, and examination of specific damage done by individually-identified primary particles.

The latter is of significance for two reasons: (1) Calculations of hit probabilities indicate that specimens sufficiently small to be flown in significant numbers are not exposed to enough radiation to cause detectable general damage. (2) The ultimate resolution of the nature of biological damage due to primary cosmic radiation at the cellular and molecular level must necessarily include an association between the type of biological damage and the nature of the physical event. This means that not only must systems be utilized which can reflect the effect of a single hit, but the system must also be amenable to a monitoring technique that will permit identification of the ionization intensity of the involved particles, e.g. nuclear emulsions.

Experiments representative of the indirect approach included studies of the longevity and cancer incidence of exposed mice† and an animal-performance study.

In considering experiments of the specific type, the biological significance of primary cosmic particles to a particular body structure depends upon the tissue's radiosensitivity, replaceability, redundancy, and genetic fate. A structure could tolerate indefinite exposure if the unique microbeam pattern of cosmic primaries causes no worse than reversible damage. Indefinite exposure should be tolerable for highly regenerative tissues such as dermis, in spite of fatal damage to cells along the path of a heavy primary track. Even nonregenerative tissue, e.g. neurons of the central nervous system, can tolerate loss equivalent to the subtle acceleration of the ageing process, if adequate alternate pathways are available. Specific tissues on which meaningful studies have been conducted to date include the central nervous system, the crystalline lens, integumental and reproductive tissue.

Experiments typical of the direct approach include Dr. Chase's black mice study, exposure of dry radish seeds, and Dr. Wilson S. Stone's genetic study of bacteria and *Neurospora*.

Results of the one indirect type of experiment completed to date have revealed no effects that would indicate a somatic health hazard from 24 hr exposure to primary cosmic radiation, but the positive effects observed make it clear that much additional experimentation will be required to be sure that longer exposures, especially of several days' duration, are safe.

Integumental studies of hair-graying primaries have been clearly demonstrated by Chase[(4)] in his observations of C57 black mice.

One of the experiments conducted on the MANHIGH II manned balloon flight was an extension of these studies relating the position of heavy

† Study conducted by Lt. Irwin Lebish under the direction of Dr. Webb Haymaker at the Armed Forces Institute of Pathology, Washington, D.C.

primaries registered by nuclear track plates to the position of gray hairs occurring on skin surface areas of the subject. Since the human subject already had marked graying of the hair on his head, an area of the dorsal surface of each forearm and an area on the right side of his chest were selected because they were free of gray hairs.

The exposure for 16 hr experienced by the subject above 90,000 ft was comparable to the exposure given black mice on previous animal experiments. Between 90,000–100,000 ft some heavy primaries will penetrate, but the number experienced would be only a fraction, approximately one-third, of the exposure to be expected at orbital altitudes in the vicinity of the earth but beyond the atmosphere.

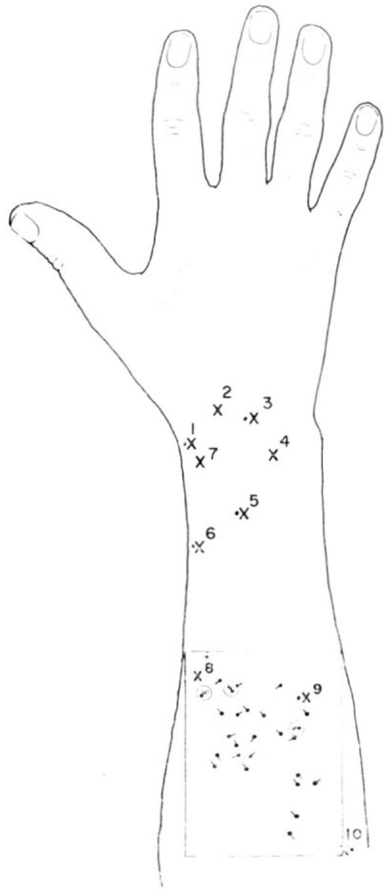

FIG. 1. The rectangular area on the right arm inclosed dots with tails to indicate medium weight primaries recorded on the nuclear track plate positioned over that part of the arm. The circled dots with forked tails represent heavy weight primaries, and the crosses represent the position of gray hairs observed on the same scale. Track plate data supplied by Dr. Herman Yagoda, AFCRC.

Monitoring Techniques

Two by three inch Ilford G5 unmounted emulsions (pellicles) were prepared in a moisture-proof, light, tight wrapping by Dr. Herman Yagoda of the Air Force Cambridge Research Center to be placed over the selected sites. Before flight the exact location of the four corners of each plate was indicated on the skin with a black tattoo mark.

Figure 1 shows the location of the tract plate on the dorsal surface of the right forearm. The plate on the left arm was in a corresponding position, and the track plate on the chest was located between the right nipple and the parasternal line (Fig. 2).

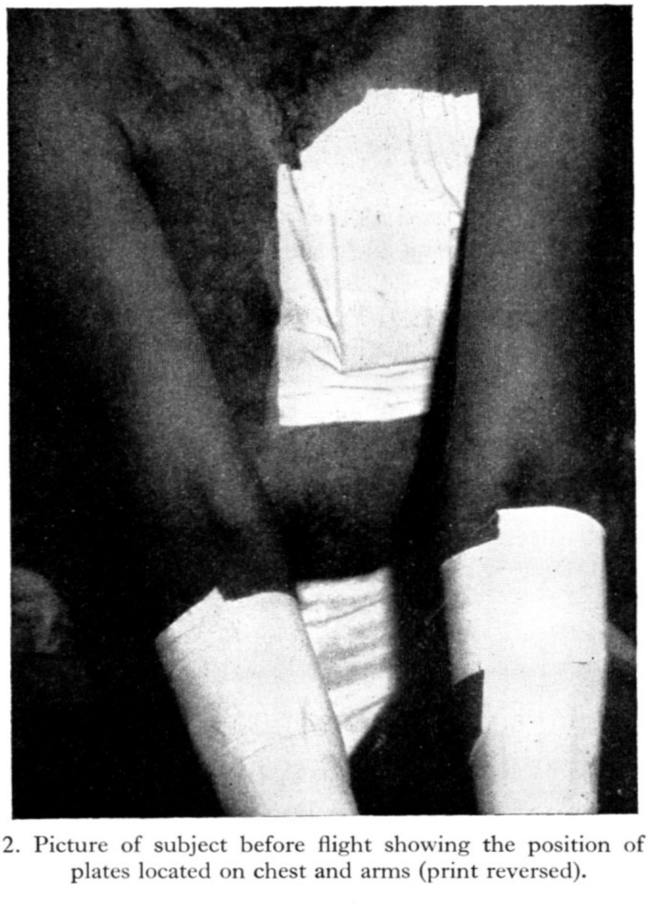

FIG. 2. Picture of subject before flight showing the position of track plates located on chest and arms (print reversed).

After flight the plates were developed and read by Dr. Yagoda and the results reported as illustrated in Figs. 3, 4, and 5. Careful examination before flight of the three selected areas revealed no gray hairs.

The pattern of gray hairs which has been observed following the flight is illustrated in Fig. 1. Numbers 1, 2, and 3 were first observed for the

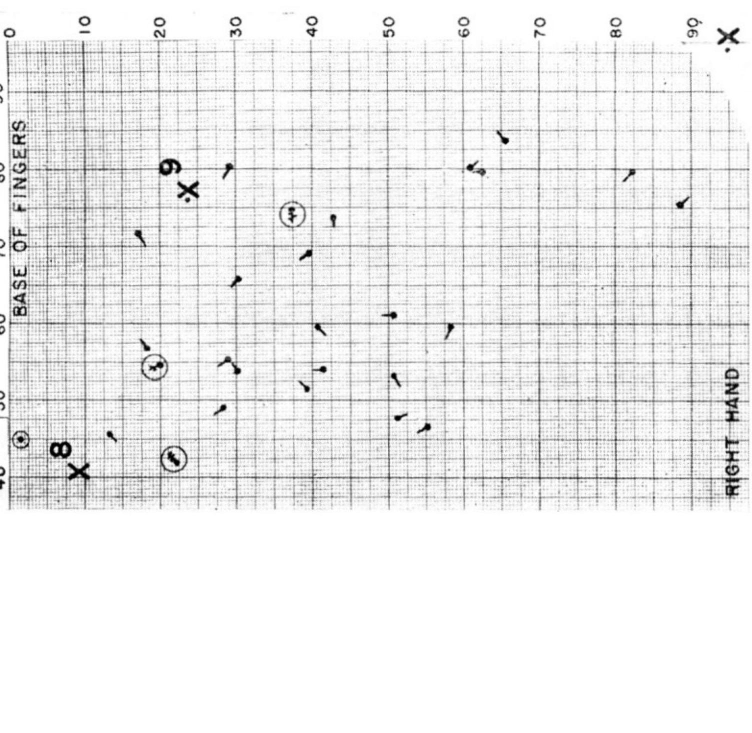

FIG. 3. Track plate data supplied by Dr. Yagoda. Locating medium and heavy weight primaries.

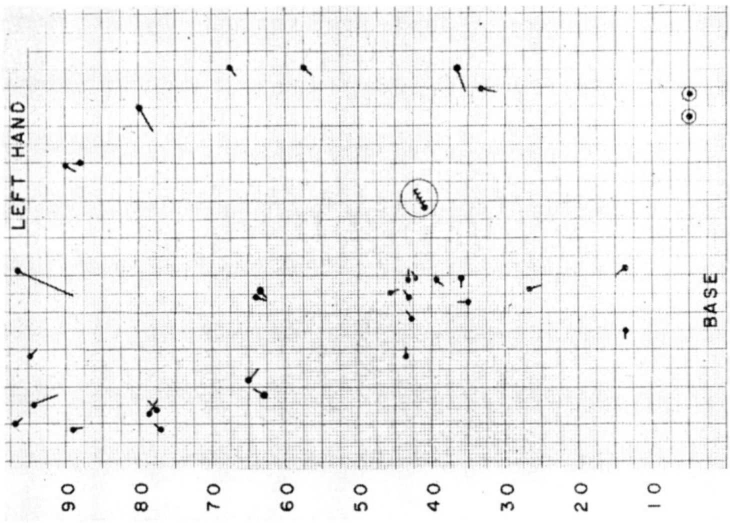

FIG. 4. Location of medium and heavy weight primaries on MANHIGH II subject's right hand. Courtesy of Dr. Herman Yagoda, AFCRC.

first time 17 September 1957. Numbers 4, 5, 7, 8, 9, and 10 were observed for the first time 31 May 1958. When the area was re-examined 1 July 1958, number 4 could not be found and number 6 had appeared.

Hairs 1, 3, 5, 6, 9, and 10 are associated with a dot adjacent to the cross representing the gray hair. Hairs in this area characteristically grow in pairs. The dot represents a normally-pigmented hair growing from a follicle immediately adjacent to a gray hair. The left arm has been repeatedly scrutinized for gray hairs, and to date none have been observed.

Immediately after flight no gray hairs were observed in the chest area monitored. On 31 May 1958 the graying pattern illustrated in Fig. 6 was observed. The corresponding track plate record is illustrated in Fig. 5.

Discussion

Gray hairs 8 and 9 located on the subject's right forearm are approximately in the path of a medium-weight primary within the limits of the accuracy of the positioning system. Number 10 may have been caused by a primary that did not penetrate the track plate since it is located just beyond the border of the plate. Unfortunately, numbers 1–6 were not monitored so there is no way of determining whether they were caused by heavy primaries or were spontaneous idiopathic gray hairs. Although the number of medium- and heavy-weight primaries penetrating the track plate on the left arm were approximately the same number as those on the right, no gray hairs have been observed.

On the right arm, twenty-eight medium- and heavy-weight primaries were recorded on the track plate. In the same monitored area only two gray hairs were observed. If this is an indication of the relative proportion of the sensitive follicle area to total skin area, it is not surprising that the thirty-four primaries recorded under the left arm may have missed hair follicles. In addition, the possibility must always be considered that the heavy primaries destroy the follicle completely, thereby eliminating the hair rather than destroying the pigment cells and producing a gray hair. No check was made to detect the absence of hairs due to this cause.

No conclusion can be drawn from the observation made of the chest area because there is obviously a marked spontaneous graying rate which would completely obscure any cosmic ray-induced graying.

A legitimate question arises as to why the graying rate observed on the right arm should be so much greater than on the left. There is no apparent reason in terms of differential shielding due to position in the capsule. It may be that the right arm is undergoing spontaneous idiopathic graying at an earlier time than in the left arm. It is barely conceivable that the left arm was fortuitously penetrated by primaries which happened to pass between the follicles. Continued observation of the rate at which gray hairs develop on the two arms may help distinguish the spontaneous graying rate from the cosmic-ray-induced graying.

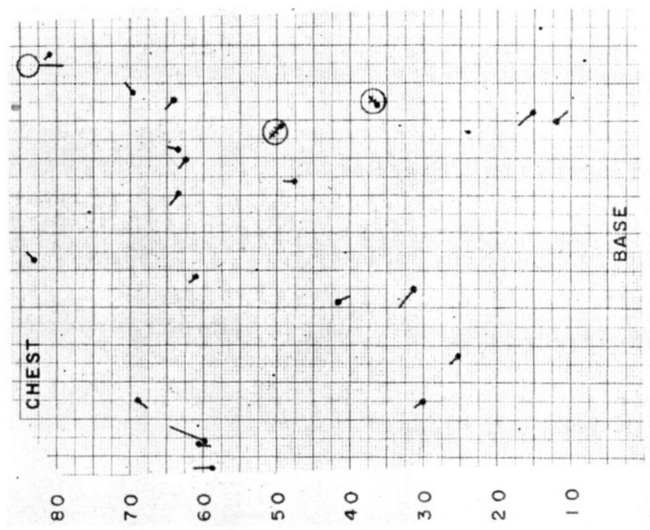

FIG. 5. Location of medium and heavy weight primaries in monitored chest area of MANHIGH II subject.

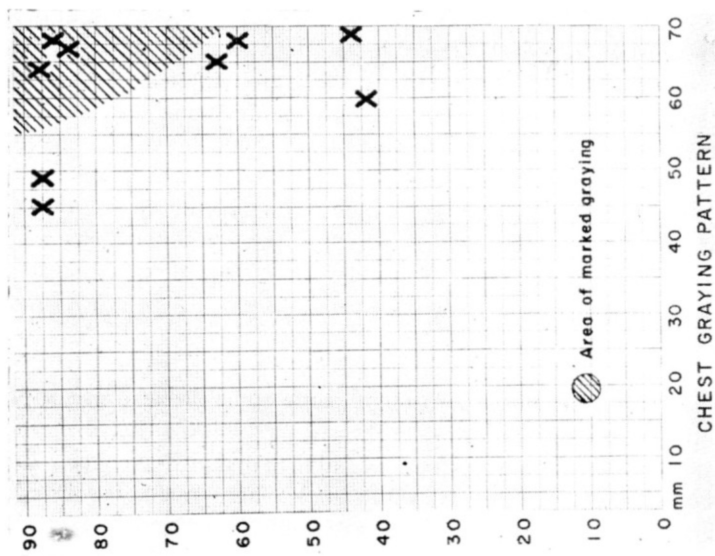

FIG. 6. Indication of gray hairs observed over the chest area using the same criteria.

Many of the serious aerodynamic problems confronting manned orbital space flight have not been considered in this discussion; only the body stresses and environments not accessible at the earth's surface were discussed. There is little doubt that the most serious hazards facing the space crewman will be found in the immediate pre- and post-vehicle launch, and finally during atmospheric re-entry and impact phases of the flight. However, until a significant human experience background in actual prolonged space flight has been achieved, absence of gravitational effects and cosmic radiation will continue to loom as mysterious and intriguing frontiers for further medical study.

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DISCUSSION

E. W. C. WILKINS*: Dr. Ward has mentioned that the greatest concentration of primary cosmic radiation occurs at about 80–100,000 ft altitude, but that the greatest concentration of secondary radiation occurs at a much lower level than this. I believe I am correct in supposing that the secondary, heavy nuclear radiation is biologically many times more of a hazard than the primary radiation, but I would like to ask the lecturer if he agrees with this. Secondly, does he consider that this radiation—either primary or heavy—is sufficient of a hazard for the aircraft designer to take it seriously in connection with passenger flight at altitudes of, say, 70,000–80,000 ft?

* Lockheed Aircraft Corpn., U.S.A.