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Heavy Cosmic-Ray Exposure of Apollo Astronauts

Abstract. *A comprehensive study of the heavy-particle cosmic-ray exposure received by the individual astronauts during the nine lunar Apollo missions reveals a significant variation in the exposure as a function of shielding and the phase of the solar cycle. The data are useful in planning for future long-range missions and in estimatting the expected biological damage.*

Unlike low-LET (linear energy transfer) radiation (such as γ and β emissions) which has always been a part of the human environment, heavy-particle, high-LET radiation and weightlessness are two unique aspects of the space environment. Recently, there has been an increasing awareness that high-LET radiation may be considerably more hazardous than the nominal absorbed doses from this type of radiation would indicate. This awareness stems in part from the fact that low-dose, high-LET radiation effects, such as light flashes in humans (*1*) and a variety of other effects in biological systems (*2*), have been observed. However, the body of information and the degree of understanding of these phenomena is meager. Thus, at this time the evaluation of possible long-term effects of such radiation, such as life shortening, carcinogenesis, or a decrease in mental or general performance during long-term missions, cannot be properly assessed and must await the results of future investigations. Although some of these effects may possibly become apparent from the observation of the exposed American and Russian astronauts, a systematic, detailed understanding of the effects of high-LET radiation will have to await the results of accelerator-based studies. Information on these effects will also be important for patients exposed to energetic heavy ions and negative pions during the experimental radiotherapy now in the planning stages at several laboratories in the United States, Europe, and Canada.

During the last several years, using plastic nuclear track detectors, we have developed methods of measuring particle parameter statistics that can be used to compute the integrated quantities of biological significance. These statistics are given in physical terms so that they will remain applicable as the biological effects of the energetic, high-Z (Z is atomic number) particles become better understood (*3–7*).

During the Apollo program, this very high-LET ($LET_{350\,ev} > 130$ kev/μm in tissue or $LET_{350\,ev} > 150$ kev/μm in Lexan) (*8*) radiation component was measured with the use of Lexan plastic nuclear track detectors. The Lexan detectors are arranged in packets consisting of three layers, each approximately 8 cm^2 in area. Each astronaut wears three packs, one each on the chest, thigh, and ankle. An additional pack is located in the film bag. Because of the small detector area and the relative insensitivity of these detectors, the particles recorded in sufficient numbers to contribute significantly to the counting statistics are those principally from the galactic cosmic-ray beam, with atomic numbers in the range $8 \leq Z \leq 26$ and having an $LET^{Lexan}_{350\,ev} \geqq 150$ kev/μm. For the most part, the particles recorded are those that stop in or near the detectors (the so-called "enders" or "thin-downs").

Although, in principle, the high-LET

Table 1. Apollo mission data; CM, command module; LM, lunar module; LS, lunar surface.

Apollo mission*	Type of mission	Launch date	Astronaut	Detector location	Total mission length (hours)	Effective mission length† (days)
8	Lunar orbiting	12-21-68	F. Borman	CM	147	5.57
			J. A. Lovell, Jr.	CM		
			W. M. Anders	CM		
10	Lunar orbiting	5-18-69	T. P. Stafford	CM, LM	192	6.59
			J. W. Young	CM		
			E. A. Cernan	CM, LM		
11	Lunar landing	7-16-69	N. A. Armstrong	CM, LM, LS	195	6.77
			M. Collins	CM		
			E. E. Aldrin, Jr.	CM, LM, LS		
12	Lunar landing	11-14-69	C. Conrad, Jr.	CM, LM, LS	244.5	8.20
			R. F. Gordon	CM		
			A. L. Bean	CM, LM, LS		
13	Lunar flyby	4-11-70	J. A. Lovell, Jr.	CM, LM	143	5.83
			J. L. Swigert	CM, LM		
			F. W. Haise	CM, LM		
14	Lunar landing	1-31-71	A. B. Shepard, Jr.	CM, LM, LS	216	7.52
			S. A. Roosa	CM		
			E. D. Mitchell	CM, LM, LS		
15	Lunar landing	7-26-71	D. R. Scott	CM, LM, LS	295.2	9.14
			A. M. Worden	CM		
			J. B. Irwin	CM, LM, LS		
16	Lunar landing	4-16-72	J. W. Young	CM, LM, LS	265.9	8.33
			T. K. Mattingly II	CM		
			C. M. Duke	CM, LM, LS		
17	Lunar landing	12-7-72	E. A. Cernan	CM, LM, LS	301.5	9.33
			R. E. Evans	CM		
			H. H. Schmitt	CM, LM, LS		

* Apollo 9 was strictly an earth orbital mission and was not included in this study. ‡ Transluna time plus one-half the lunar orbit plus the transearth time.

Table 2. Planar fluences derived from a least squares analysis (particles per square centimeter with $LET_{350\ ev}$ > 150 kev/μm in Lexan).

Apollo mission	Command module pilot (only in spacecraft)			Command and lunar module pilot (also on lunar surface)				Geometric mean fluence	Geometric mean flux* (cm^{-2} day^{-1})
	Chest	Thigh	Ankle	Chest	Thigh	Ankle	Film bag		
8	2.3 ± 0.4	2.6 ± 0.4	3.2 ± 0.5				8.2 ± 0.9	3.2 ± 0.5	0.58 ± 0.09
10	2.8 ± 0.3	3.2 ± 0.4	3.9 ± 0.4				6.5 ± 0.7	4.0 ± 0.3	0.61 ± 0.05
11	2.4 ± 0.3	2.8 ± 0.4	3.4 ± 0.4	3.5 ± 0.3	3.2 ± 0.3	3.9 ± 0.4	5.5 ± 0.6	3.4 ± 0.3	0.50 ± 0.04
12	3.3 ± 0.4	3.7 ± 0.4	4.5 ± 0.5	4.7 ± 0.4	4.2 ± 0.4	5.2 ± 0.4	7.4 ± 0.8	4.6 ± 0.4	0.56 ± 0.05
13	3.1 ± 0.4	3.5 ± 0.5	4.3 ± 0.5	4.4 ± 0.5	4.0 ± 0.5	4.9 ± 0.5	7.1 ± 0.9	4.3 ± 0.5	0.74 ± 0.09
14	4.4 ± 0.5	5.1 ± 0.6	6.1 ± 0.6	6.3 ± 0.5	5.8 ± 0.5	7.1 ± 0.6	10.1 ± 1.0	6.2 ± 0.5	0.83 ± 0.07
15	6.0 ± 0.7	7.9 ± 0.8	9.6 ± 1.0	9.9 ± 0.7	9.0 ± 0.6	11.1 ± 0.8	15.8 ± 1.3	9.7 ± 0.6	1.07 ± 0.07
16	8.2 ± 0.9	9.3 ± 1.1	11.3 ± 1.2	11.7 ± 0.9	10.7 ± 0.9	13.1 ± 1.0	18.7 ± 1.8	11.5 ± 0.9	1.38 ± 0.11
17	9.4 ± 0.8	0.7 ± 1.0	13.0 ± 1.0	13.4 ± 0.7	12.2 ± 0.7	15.0 ± 0.7	21.4 ± 1.3	13.2 ± 0.5	1.41 ± 0.05
	Position factor								
	0.71 ± 0.05	0.81 ± 0.06	0.98 ± 0.06	1.02 ± 0.05	0.93 ± 0.05	1.14 ± 0.05	1.63 ± 0.05		

* The mean fluence divided by the effective mission length (Table 1).

particle fluxes can be theoretically evaluated from the external cosmic-ray beam, the variability in the cosmic-ray flux at low energies due to solar modulation, the extremely complicated and variable shielding configuration for each astronaut, and the lack of knowledge of nuclear fragmentation parameters preclude accomplishing this task with any degree of accuracy. Thus, in practice, it is necessary to measure the heavy-particle fluxes at the various positions of interest so that these data become a part of the overall medical record of each astronaut and are then available for future assessments.

The experimental data reduction and analysis procedures are similar to those described in earlier reports on Apollo flights 8 through 14 (*4*), 15 (*5*), 16 (*6*), and 17 (*7*). A more detailed account of the data reduction is presented in (*4*).

The relevant data on Apollo missions 8 through 17 are listed in Table 1. It was assumed that the earth's magnetic field excludes all registrable particles for the earth orbit phase.

To consolidate all the measured fluences and provide additional averaging, a model to compute the particle fluences was developed. It was found that the measured fluences could be represented to within 1.4 times the errors in the counting statistics if the reduced particle fluence was given in terms of a product of two factors: (i) the geometric mean fluence for the mission and (ii) a factor dependent on the position (shielding) of the detector during the mission, called the position factor. We determined the values of these factors from the measured fluences, using a least squares procedure (*9*).

The results of the particle fluence model described above are listed in Table 2. The fluence values (in tracks per square centimeter) for the different missions, divided into two groups, are listed in the central portion of the table. The groups represent the two different shielding environments: that of the command module pilot who remained always in the spacecraft and that of the commander and lunar module pilot who spent a portion of the total time on the lunar surface. The detectors in the film bag are included in the latter category.

Through the use of the modeling procedure, it was possible to fill in the missing data (on nearly all missions several detectors were not recovered), and to make meaningful intercomparisons of the absolute track fluences on different missions.

From Table 2 it is clear that, with the progress of the Apollo program, there has been a steady increase in the heavy-particle, high-LET exposure of the astronauts. The data also clearly demonstrates the importance of shielding, including self-shielding, on the high-LET exposure:

1) The command module pilot who remains in the spacecraft invariably received a smaller exposure than the commander and the lunar module pilot.

2) The least-shielded position, the ankle, received a higher exposure than the chest position for which there was greater shielding. The exposure of the thigh position is intermediate. The shielding referred to here is self-shielding. It is assumed that the effects of the external spacecraft shielding average out in time for all the detector positions on the astronauts while they are in the spacecraft.

3) The effect of shielding is also clearly indicated by the detectors stored in the film bag. The film bag position consistently received the highest exposure on each of the nine Apollo missions, more than twice the particle exposure measured on the chest detectors of the astronauts remaining in the spacecraft. The sensitivity of the high-LET exposure to shielding is in contradistinction to the insensitivity of the proton exposure as measured with nuclear emulsions (*10*) and thermoluminescent dosimeters (*11*). This observation is in agreement with the theoretical predictions of Curtis and Wilkinson (*12*).

4) A sharp rise in the high-LET exposure is evident starting with the Apollo 14 mission. This is due in part to the longer mission times.

5) The variation in mission flux is significant (see the last column of Table 2), with the flux during Apollo missions 16 and 17 being some ~2.4 times higher than that of Apollo missions 8 through 12. A comparison of the measured particle fluxes with computed fluxes based on the Mount Washington, New Hampshire, neutron counting rate shows that the measured variation of the particle fluxes is attributable to solar modulation of the primary cosmic-ray beam.

The results presented here should be compared with those of Fleischer *et al.* (*13*) who used Apollo 8 and Apollo 12 Lexan helmets, the Lexan electrophoresis experiment from Apollo 14, and the Apollo 16 cosmic-ray experiment package to make heavy-particle dosimetry comparisons. They report that solar modulation was responsible for a variation of a factor of 5 in the heavy-particle track-production rate from Apollo 8 to Apollo 16 (*13*). This is in significant disagreement with our results; from Table 2, the observed increase in the flux between Apollo 8 and Apollo 16 is a factor of ~2.4. There are a number of fundamental differences between the two sets of measurements. These include the differences between the detectors used, detector shielding, and differences in processing conditions. It is probable that the greatest difference was produced by the differences in shielding. The similarity in the shielding conditions experienced by our detectors and the averaging carried out in the modeling procedure help eliminate variability due to differences in shielding. The use of a single batch of Lexan on all missions, with a single processing cycle which included detectors from all nine missions, combined with a data acquisition carried out by the same observers, gives us a high level of confidence in the results reported here.

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8 The response of plastic nuclear track detectors more closely follows the $LET_{350\ ev}$ rather than the LET_{∞} of particles. For this reason the quantity $LET_{350\ ev}$ is used throughout this work. Over a wide range of particle velocities $LET_{350\ ev}$ can be converted to LET_{∞} if one multiplies by a factor of ~ 1.6.
9. For details of this procedure and the measured fluences, please write to the authors.
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Self-Produced Locomotion Restores Visual Capacity after Striate Lesions

Abstract. *Rats permitted unrestrained movement in a patterned visual environment during the interval between two-stage bilateral lesions of the visual cortex reacquire a preoperatively learned pattern discrimination. Rats passively transported through the identical visual environment do not. This is the first demonstration that interoperative self-produced locomotion is essential for recovery of function in the visual system.*

Recovery of preoperatively learned tasks occurs in mammals when the brain areas relevant to the task are removed serially (*1*). Identical ablations or lesions made in a single operation may retard recovery of the task or prevent its reacquisition. Recovery is dependent upon the length of the interoperative interval (*2*), the size of the lesion (*3*), and the type of sensory stimulation experienced during the interoperative period (*4*). If animals subjected to two-stage lesions of the visual cortex are kept in the dark between surgeries, loss of visual function occurs just as though the ablation were performed in one stage. On the other hand, animals receiving various types of visual stimulation during the interoperative period recover visual capacity to varying degrees.

The nature of the interoperative experience is the subject of this research. Exactly what types of interoperative stimulation are required for complete recovery of visual function remained in question, but some clues were provided from a parallel area of research: neonatal visual deprivation.

In young animals, visual deprivation early in life precludes normal development of visual function (*5*). Furthermore, self-produced movement must accompany exposure to the visual environment for development of pattern vision. In view of this literature, we decided to investigate the effects of various kinds of sensory-motor deprivation upon the restoration of pattern vision after serial lesions of the striate cortex in rats. The data presented here demonstrate that self-produced movement is requisite for the recovery of pattern vision.

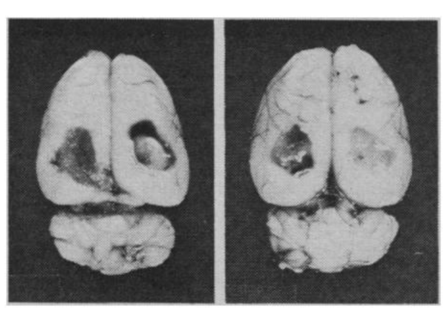

Fig. 1. Maximal (rat No. 6) and minimal (rat No. 23) cortical damage. Mean destruction was 14.6 percent of neocortex for all groups.

Fifty-two adult male Long-Evans rats were tested for ability to discriminate horizontal-vertical patterns, were given two-stage ablations of the striate cortex, and were retested for ability to discriminate visual patterns. During the 11 days between two-stage surgeries, the subjects were exposed differentially to visual stimulation 4 hours daily. The remaining 20 hours were spent in total darkness.

Rats were trained in a modified Thompson-Bryant Box (*6*). Prior to surgery, the animals underwent 5 days of pretraining consisting of ten trials per day. During days 1 and 2, the rats were taught to run to the goal box to escape or avoid shock. Over days 3, 4, and 5, two white translucent doors were gradually lowered over the goal box openings, and the rats were trained to push through the doors to enter the goal box.

The animals were then taught to discriminate between a vertical black-white striped door which led to the goal box and a horizontal black-white striped door which was always locked. The position of the correct door was varied randomly. Upon the lifting of the start gate, the animal was required to run through the vertically striped door into the goal box within 10 seconds to avoid or escape a constant-current, 1-ma shock of 2-msec duration, three times per second. A response to the negative stimulus was always shocked. Such a response involved the animal entering the wrong alley by two or more inches (5 cm). Preoperatively, animals were discarded if they failed to reach the criterion of nine out of ten correct discriminations within 12 days. Postoperatively, animals were run to an upper limit of 20 days to the same criterion. Recordings were made of the number of discrimination trials to cri-