the third had glutaraldehyde as a fixative. The whole tray assembly was sealed in a plastic bag.

Materials and methods are described in Table 1 for each pack. The experimental conditions are listed in Figure 2b.

RESULTS

Figure 2c shows attachment of single cells and a large clump of cells for a sample fixed 12 hours after mixing of cells and beads on orbit. At ambient temperature the attached cells did not flatten or grow on bead surfaces. To evaluate the number of beads with cells attached, beads were arbitrarily divided into three categories; 1) beads with no cells, 2) beads with 1-10 cells and, 3) beads with clumps of cells attached. Each of the bead packs was divided into two aliquots for counting. Table 2 shows results of bead counts.

TABLE 2. CELL ATTACHMENT TO BEADS UNDER MICROGRAVITY CONDITIONS

CELL BEAD PACK # AND ALIQUOT	FIXED AT TIME (Hrs)	BEADS WITH 0 CELLS		BEADS WITH 1-10 CELLS		BEADS WITH CELL AGGREGATES		TOTAL NUMBER OF BEADS COUNTED
		NO.	MEAN % OF TOTAL COUNT ± SD	NO.	MEAN % OF TOTAL COUNT ± SD	NO.	MEAN % OF TOTAL COUNT ± SD	
1 A	12	55	84 ± 6	14	16 ± 6	ND	ND	69
B		117		16		ND		133
2 A	24	102	70 ± 14	47	20 ± 11	21	20 ± 11	170
B		91		14		9		114
3 A	33	114	60 ± 0	42	25 ± 4	34	25 ± 4	190
B		109		40		30		179
4 A	48	151	64 ± 4	42	18 ± 0	36	18 ± 0	229
B		114		34		40		188

By 12 hours after mixing cells and beads on orbit, 84% of beads counted had no cells and 16% of beads already had 1-10 cells. As time increased up to 33 hours, the number of beads with no cells decreased as the number with 1-10 cells and clumps of cells increased. No mixing was performed after the initial procedure at time zero. This confirmed that cells attach to growth surfaces while free floating in suspension under microgravity conditions. By 48 hours under less than optimal conditions of temperature, no statistical increase in cells attached to beads was apparent. Ground based experiments showed similar results.

CONCLUSIONS

Clearly, epithelial human kidney cells can attach to microcarrier beads under microgravity conditions even though the opportunities are based on initial mixing and thereafter to random collisions due to Brownian motion of the cells during the experiment period.

In ground based simulations, cells which were incubated at 37° C attached to beads, flattened on the bead surfaces, and began to grow. This indicated that the cells used in this experiment were viable and grew normally under optimal conditions. The aggregation of cells to cells was not an artifact of the glutaraldehyde fixative. In ground based experiments fixed at 24 and 72 hours after mixing cells and beads hardly any clumping was observed. This finding suggests that clumping may be due to a microgravity effect or to cell-cell interaction in the syringes during launch and orbit insertion prior to mixing cells with beads on orbit. It was apparent that the cells attach to each other if beads were not available. It was also obvious that considerable attachment occurred in the first 24 hours of this experiment. Under normal incubator temperatures cell metabolism would be greater, therefore, cell attachment may be even more pronounced.

This DSO was successful in that it met the objective of the experiment. Cells were shown to attach to growth surfaces in microgravity. Recommendations for the next flight DSO experiment included: (1) optimizing cell survival conditions by mixing cells and beads in culture chambers in a 37° C cell culture incubator, (2) designing the experiment to quantitate the relative attachment which occurs in the first 24 hours after mixing cells and beads on orbit, (3) counting larger numbers of cells and beads for statistical analyses post flight, and (4) evaluating the way in which cells are attached to beads by scanning electron microscopy.

INCUBATOR CELL ATTACHMENT TEST (ICAT)

Investigators: Dennis R. Morrison, Ph.D., Marian L. Lewis, Ph.D., A. Tschopp, Ph.D., and A. Cogoli, Ph.D.

INTRODUCTION

The microgravity environment of space provides unique advantages for the production and purification of pharmaceutical type natural cell products. Because of the potential of space bioprocessing, there is a new requirement to assess the behavior of cells in microgravity. Eventually, cells will be cultured in space in bioreactors and the desirable cell products will be harvested, purified and returned to Earth. Many of the target products, such as urokinase, are produced by cells which survive and grow only when attached to a substratum.

The attachment of cells to growth surfaces on Earth is normally affected by the settling of cells onto surfaces of flasks or other culture vessels. The experiments reported herein were designed simply to answer the fundamental questions: Do cells a) attach to and b) proliferate on growth surfaces as well in microgravity as on Earth.

Feasibility of cell-to-bead attachment at ambient temperature was shown on STS-7. The STS-8 Incubator Cell Attachment Test (ICAT) represented a cooperative effort between NASA and European Space Agency scientists. The test was initially designed to check out the Carry-on Incubator, developed and manufactured at the E. T. H. - Zentrum Zurich, Switzerland, before it was used for a lymphocyte experiment on Spacelab-1 and to assess cell attachment efficiencies at normal culture temperatures. On STS-8, kidney cells and microcarrier beads were incubated at 37° C in the carry-on incubator. The attachment of the kidney cells to beads is the subject of this report.

PROCEDURES

INCUBATOR

The apparatus, described in detail elsewhere (Cogoli and Tschopp, 1982), consisted of a carry-on box capable of maintaining a temperature of 37° C either with batteries or with on-board power, and which could be fixed to a front panel installed in the Space Shuttle's flight deck (Figure 1) or in a rack of the Spacelab module. The incubator contained four cell culture chambers sealed with a mobile piston, four syringes loaded with the microcarrier beads and four syringes with glutaraldehyde as fixative (Figure 2).

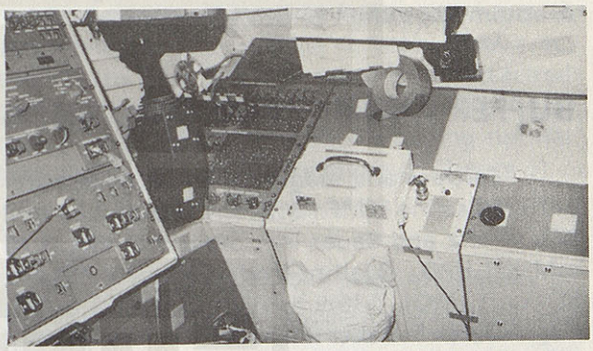


Figure 1. Incubator in place - Orbiter flight deck.

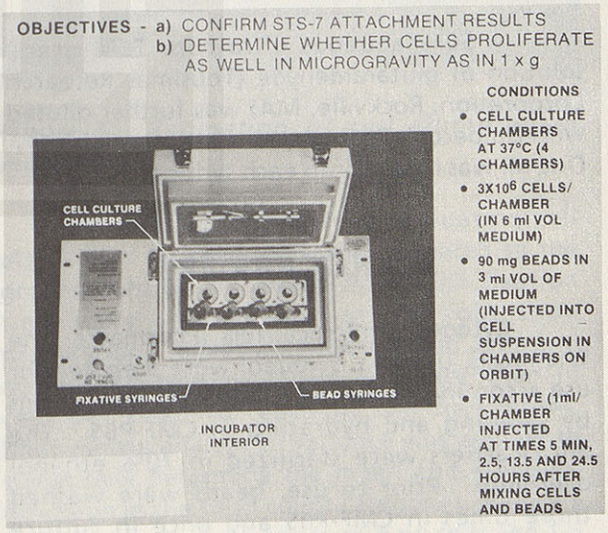


Figure 2. STS-8 ICAT.

CELLS AND MEDIUM

Frozen suspensions of human embryonic kidney cells were purchased from M. A. Bioproducts, Walkersville, MD. The cells were grown in medium consisting of one part each of Medium 199, MEM alpha, and Dulbecco's Modified Eagle Medium (Gibco Laboratories, Grand Island, NY) supplemented with 1.2 g/L of bactopeptone (Difco Laboratories, Detroit, MI), 0.02 g/L of folic acid, 0.72 g/L of i-inositol, 0.1 g/L of nicotinic acid, 16.2 g/L of NaHCO (Sigma Chemical Co., St. Louis, MO), 10% fetal bovine serum (Biolabs, Northbrook, IL), 20 mM HEPES (Research Organics Inc., Cleveland, OH) and 100 units/ml of penicillin and 100 mg/ml of streptomycin sulfate (Gibco Laboratories).

BUFFER AND ENZYME SOLUTIONS

Calcium and magnesium-free phosphate-buffered saline (CMF-PBS) consisted of 2.65 mM KCL (Pfaltz and Bauer Inc., Stamford, CN), 1.46 mM KH_2HPO_4 (Mallinckrodt Chemical Works, St. Louis, MO), 136.9 mM NaCl and 8.0 mM Na_2HPO_4 (J. T. Baker Chemical Co., Phillipsburg, NJ). Trypsin (Gibco Laboratories) and EDTA (Sigma Chemical Co.) were combined at 0.05% each in CMF-PBS.

GLUTARALDEHYDE FIXATIVE

A 50% aqueous ultra-pure TEM grade solution of glutaraldehyde (Tousimas Research Corporation, Rockville, MA) was further diluted with Dulbecco's PBS' to a concentration of 2.5%. One ml was loaded into each syringe.

MICROCARRIERS

Cytodex 3 microcarriers (Pharmacia Fine Chemicals, Uppsala, Sweden) were prepared for use according to the manufacturer's instructions by swelling and hydrating in CMF-PBS. The microcarriers were sterilized in 70% ethanol overnight. Prior to use, beads were washed three times in CMF-PBS and once in culture medium. The microcarriers were suspended in culture medium at a concentration of 30 mg/ml and loaded into the syringes.

GROUND PROCEDURES

Preflight operations were performed in the Life Sciences Payloads Facility at NASA Kennedy Space Center. Cells at passage level one were used for the experiment. The cells, previously grown in primary culture and stored frozen, were thawed, suspended in culture medium and planted in 75 cm^2 growth surface flasks (Corning 25110) five days prior to the scheduled time of stowage on the Shuttle. At launch time T-14 hrs, cells were approximately 90% confluent and were removed from flask surfaces with trypsin-EDTA. The cells were suspended in culture medium at a concentration of 464,000 cells/ml, and 6 ml of the cell suspension were then pipetted into each of the four cell culture chambers. Ground-based control cells were prepared in the same manner as for flight. The ground control experiment was run at NASA Johnson Space Center, Houston, TX.

FLIGHT PROCEDURES

The incubator with cultures and syringes was installed on board 14 hrs before launch and kept at ambient temperature. Four hrs after launch the incubator was switched on and 3.5 hrs later the experiment was started by injection of the beads into the cell chambers. Samples 1-4 were fixed by injection of glutaraldehyde 5 min, 3 hrs, 13.5 hrs and 24.5 hrs after addition of the beads espectively. Finally the incubator was switched off and the samples remained stored within the incubator until the end of the mission 6 days later. They were returned to the investigators 6 hrs after landing of the Shuttle and transported to the Bioprocessing Laboratory at the Johnson Space Center in Houston.

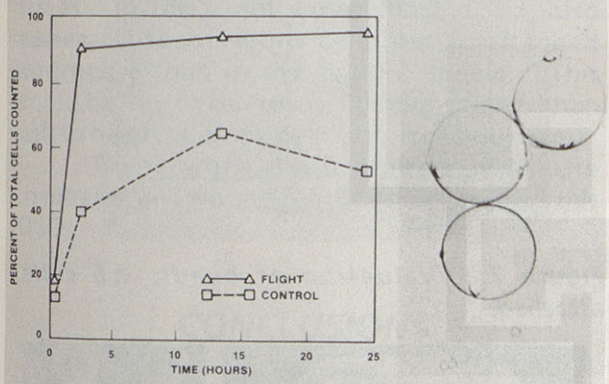
RESULTS

After return of the incubator to the laboratory, the cell/bead suspensions were removed from the growth chamber. An aliquot was taken from each suspension for scanning electron microscopy and the remaining suspension was evaluated for cell to bead attachment, cell-cell aggregation and individual

floating cell counts. For cell and bead counts, four slides were prepared for each sample fixed at each of the four times after mixing cells and beads on orbit or in the ground control. Figure 3 shows the ratio and percent of single (not clumped) cells counted which were attached to beads at each time. Significantly more single cells attached at each fixation time in the flight experiment than in the ground control. Statistical analyses of the cell counts were done by the non-parametric procedure of Cochran.

FIXATIVE ADDED

CHAMBER NO.	AT TIME AFTER MIX. CELLS AND BEADS (HOURS)	FLIGHT	% OF TOTAL	GROUND	% OF TOTAL
1	0.083	56/300	18.7	40/300	13.3
2	2.5	215/236	91.9	41/100	40.0
3	13.5	147/154	95.0	65/100	65.0
4	24.5	76/79	96.0	53/100	53.0



- FLIGHT - SIGNIFICANTLY MORE SINGLE CELLS ATTACHED AT EACH SAMPLE TIME (STATISTICAL ANALYSIS BY NON PARAMETRIC PROCEDURE OF COCHRAN)
- THIS DATA SUPPORTED BY BEAD EVALUATIONS

Figure 3. Attached single cell counts.

The number of cells per clump in aggregates which were not attached to beads is shown in Figure 4. In the ground control, by 2.5 hours only eight unattached clumps of cells were counted in the four prepared slides. In the flight samples, there were approximately three times more unattached clumps and there appeared to be more cells per clump. In 1-G the clumped cells tended to settle rapidly and had an opportunity to adhere to beads; whereas, in microgravity clumps free-floated until coming into contact with a bead. It appeared that cell-to-cell clumping occurred more frequently in flight than on the ground at the 2.5 hour time.

		0.083 HOURS	2.5 HOURS	13.5 HOURS	24.5 HOURS
GROUND CONTROL	NO. OF CLUMPS	261.00	8.00	1	ND
	MEAN CELLS/CL	4.11	2.88*	6	ND
	STANDARD DEV.	3.15	1.36	0	ND
FLIGHT	NO. OF CLUMPS	141.00	25.00	19.00	8.00
	MEAN CELLS/CL	3.48	8.44*	4.26	3.25
	STANDARD DEV.	2.45	6.23	3.48	1.49

*AT 2.5 HOURS - FLIGHT, MORE CELLS/CLUMP THAN CONTROL. INTERESTING IF DUE TO STICKY FLIGHT CELLS ATTACHING TO ONE ANOTHER IF NO BEADS AVAILABLE IN VICINITY.

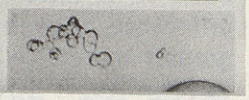


Figure 4. Number of cells/clump (unattached).

There was no significant difference in the number of cells attached to beads per clump of aggregates in flight versus control. However, statistically the average number of attached cells per clump in both the flight and ground control increased with time, indicating normal growth once the cells were attached (Figure 5).

- NUMBER OF CELLS/CLUMP ATTACHED - NO SIGNIFICANT DIFFERENCE FLIGHT VS. CONTROL
- AVERAGE LOG OF NUMBER OF CELLS/CLUMP ATTACHED INCREASED WITH TIME - INDICATES SOME CELL GROWTH FLIGHT AND CONTROL

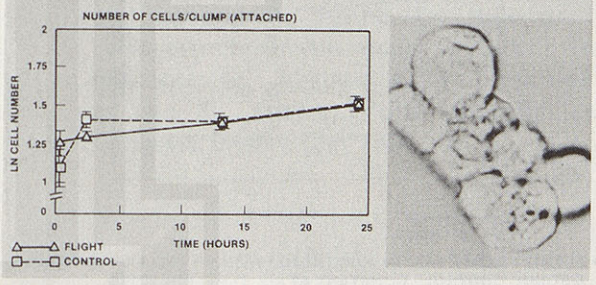
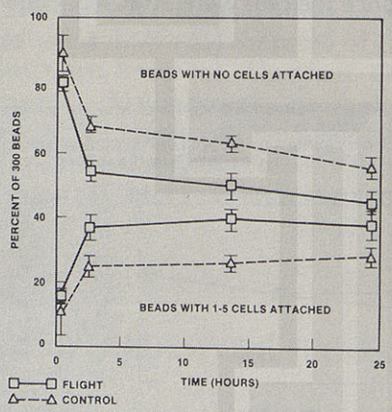


Figure 5. Estimation of cell clumping in microgravity.

As another approach to evaluating cell attachment to beads in flight compared to the ground control, 300 beads from each fixation time were scanned on each of four slide preparations. Beads were categorized as having no cells, 1-5 cells, 6-10 cells, or greater than 10 cells per bead for each of the four slides. Multivariate analysis of variance was applied to statistically determine the mean and standard deviation in the bead count categories. Figure 6 shows evaluations of beads with no cells and 1-5 cells per bead. The flight experiment had significantly more beads with 1-5 cells than the ground control. The number of beads with no

cells decreased with time as those with 1-5 cells increased. For categories of 6-10 and greater than 10 cells per bead there were very few beads; thus, there were large standard deviations for counts of the four replicate slides (Figure 7). The trend of the mean counts indicates an increase in the number of cells per bead with time. There was no significant difference between flight and control in the greater than 5 cells per bead categories. To determine if there were morphological differences in the way cells attached between flight and ground samples, scanning electron micrographs were examined. Figure 8 reveals no discernible differences between flight and ground samples. In both cases, the cells attached, flattened and increased in number as shown by the almost confluent state of some beads.

A TOTAL OF 300 BEADS WERE SCANNED PER SLIDE AND CLASSIFIED AS HAVING 0, 1-5, 6-10 OR > 10 CELLS/BEAD. (MEAN AND STANDARD DEVIATION OF FOUR SLIDES) (STATISTICS - MULTIVARIATE ANALYSIS OF VARIANCE.



- FLIGHT - SIGNIFICANTLY MORE BEADS WITH 1-5 CELLS/BEAD THAN GROUND CONTROL - CONSTANT AT ALL SAMPLING TIMES
- BEADS WITH NO CELLS DECREASED AS NUMBER OF BEADS WITH 1-5 CELLS/BEAD INCREASED

Figure 6. Evaluation of beads, ≤ 5 cells attached.

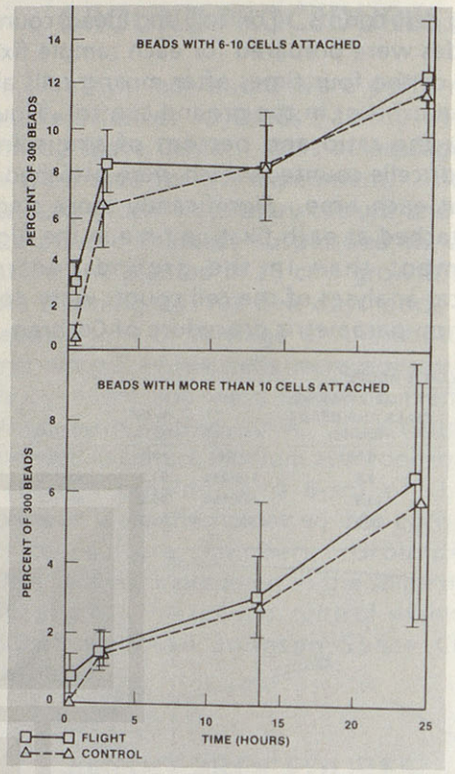


Figure 7. Evaluation of beads, ≥ 6 cells attached.

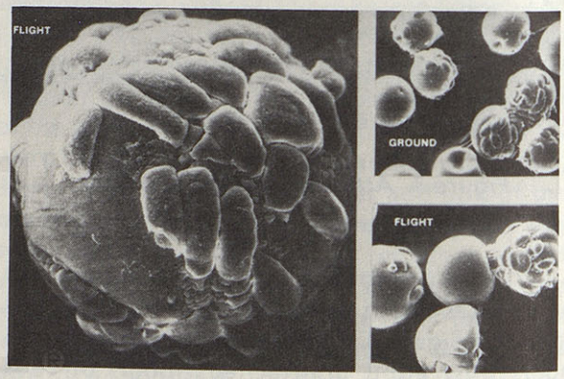


Figure 8. Scanning electron micrographs of cell/bead attachment fixed 24.5 hours after mixing cells and beads.

DISCUSSION / ANALYSIS

One concern was that cell attachment would be less in microgravity since the only opportunity for contacts between cells and beads would be based on random collisions while floating free in the culture chambers. These results show very clearly that considerable

attachment occurs quite quickly when cells and beads are mixed together in microgravity. At 37° C the number of attached cells was higher in the flight samples than in the ground control. This was possibly due to greater surface area availability at low-g, since all surface area of the beads would be available to cells, while on Earth only the top hemisphere of settled beads is available. Most of the cell adhesion occurred within the first 3 hr, and cell growth and replication appeared normal after cells had attached to microcarriers. Unspecific adhesion of cells by covalent attachment through an activation of the Cytodex carriers by glutaraldehyde can be excluded. If the attachment were nonspecific there would not be a difference between counts at the different times. In the flight experiment, there also appeared to be more cells per unattached aggregate than in the ground control. This could be due to cell to cell collisions rather than cell to bead collisions, resulting in cell clumping.

There were no problems with the incubator and no malfunctions occurred in this DSO.

CONCLUSIONS

Results of this DSO show clearly that anchorage-dependent human kidney cells attach to beads as well, or better, in microgravity than on Earth. Fifty percent more single cells had attached by 2.5 hours than in the ground control. There were no apparent differences in cell spreading and proliferation on the beads and no discernable differences in the manner of attachment observable by scanning electron microscopy.

These findings are extremely significant to the future of bioprocessing in space. They show that cells may be seeded on beads and initiated in microgravity for culture in a bioreactor or that cells may be grown in microgravity for electrophoretic separations. The selected subpopulations of high product-secreting cells may be seeded on beads for production of target pharmaceuticals. Cells separated by continuous flow electrophoresis may now be collected in receptacles containing microcarrier beads, thereby allowing attachment and better survival while the samples are waiting for return to Earth-based laboratories for culture and analyses.

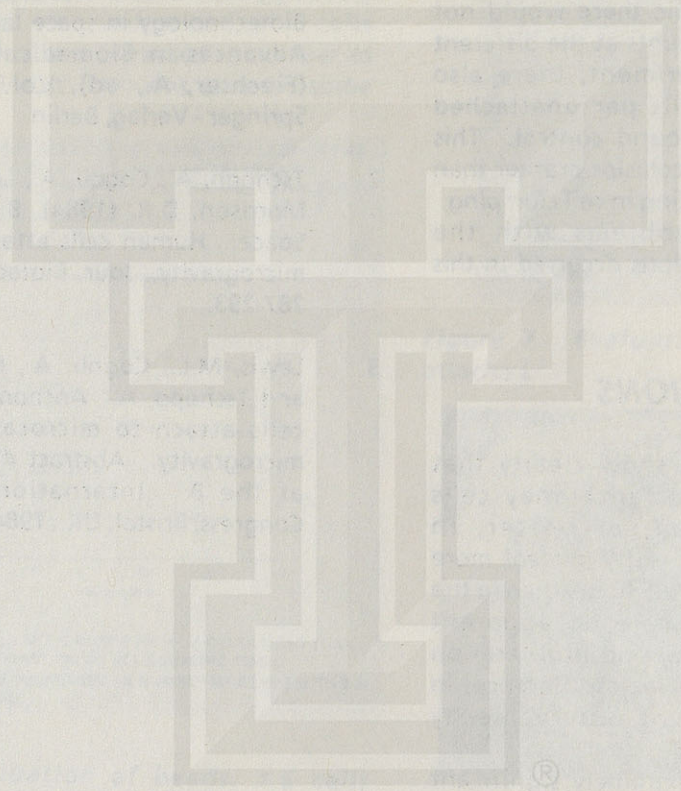
Recommendations for further study include flying other DSOs to investigate effects of long term culture of cells on beads in microgravity, secretion of target products, effects of microgravity habitation on the cytoskeleton, and secretion of attachment proteins.

PUBLICATIONS BASED ON THIS DSO

1. Cogoli, A. and Tschopp, A. (1982). Biotechnology in space laboratories. In: Advances in Biomedical Engineering (Fiechter, A., ed), Vol. 22, pp. 1-50 Springer - Verlag, Berlin.

2. Tschopp, A., Cogoli, A., Lewis, M.L., and Morrison, D.R. (1984). Bioprocessing in Space: Human cells attach to beads in microgravity. Jour. Biotechnology (1984) 287-293.

3. Lewis, M.L., Cogoli, A., Morrison, D.R., and Tschopp, A. Anchorage dependent cells attach to microcarrier beads in microgravity. Abstract #263 - presented at the 8 International Biophysics Congress, Bristol, UK., 1984.



MICROBIAL SCREENING

Investigator: Duane L. Pierson, Ph.D.

INTRODUCTION

Microbial contamination during spaceflight presents a variety of health hazards to the crew and deterioration of essential materials. The level of airborne microbial contaminants has been established as an important factor in the dissemination of infectious diseases. The Shuttle/Spacelab serves as a small closed environmental system with a limited ability for the removal of airborne microbes. Microbially laden droplets and particulates generated by coughs, sneezes, and crew activities are removed from the air in minutes at one g; however, these droplets can remain suspended for hours in microgravity.

The JSC Microbiology Laboratory implemented a Microbial Contamination Control Plan at the onset of the STS missions. One facet of the plan was the quantitation and identification of airborne microbial contaminants. The cabin air was evaluated preflight and postflight to assess the efficacy of the environmental control system in removing such contaminants. The presence of an open hatch and the activities of various ground support personnel during sample collection jeopardizes the scientific validity of such studies. Inflight monitoring was the only scientifically sound method for assessing the levels and types of airborne microbial contaminants during a mission. The impact of the length of mission, number of crewmembers, and the inclusion of animals and other biological specimens upon the microbial load of the Orbiter's air can be assessed only by the evaluation of inflight air samples.

PROCEDURES

Evaluation of the airborne microorganisms was achieved by the use of the Reuter Centrifugal Air Sampler (RCS). Two-minute air samples were taken with the RCS using trypticase soy agar strips or rose bengal agar strips. Samples were taken during the preflight, inflight, and postflight phases of the missions. The sample sites were located on both the mid-deck and the flight deck. The microorganisms collected on all air strips were quantitated and identified.

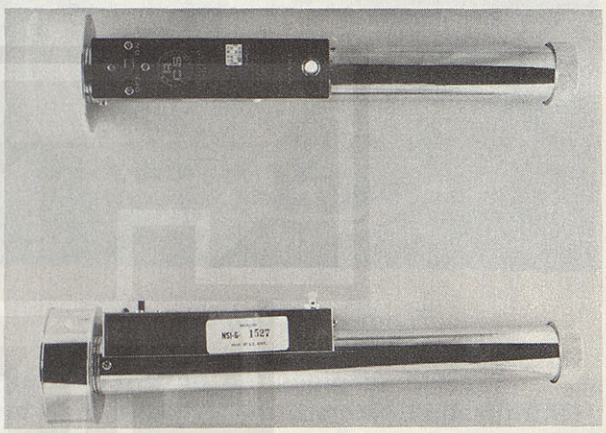


Figure 1. The Reuter Centrifugal Air Sampler.

The RCS is a completely portable instrument which can be hand-held and requires relatively little maintenance. The body consists of a metal tube 336.5 cm in length and 3.8 cm in diameter with an open end drum on one end, a power pack attached to the side, and a screw cap for access to the batteries on the end opposite the drum (Figure 1). The power pack is 3.5 cm X 13.9 cm X 1.3 cm and has an indicator light, main power ("ON-OFF") switch, time settings, and a start button. The indicator light detects weak or nonfunctioning batteries when the "ON-OFF" switch is in the "ON" position. The time setting selectors determine the length of time the sampler will run and the volume of air that will be sampled. The open end drum assembly is 7 cm in diameter and 3.2 cm deep and houses a removable ten blade impeller (Figure 2). The impeller blade assembly is removed for cleaning and/or sterilization as required by gently pulling on the knob attached to the center of the blade assembly; the drum can then be unscrewed from the instrument.

The inside of the drum is grooved to hold the agar strip in place.

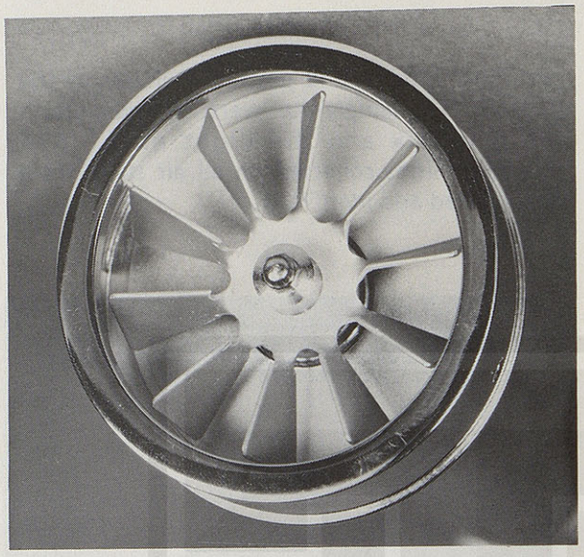


Figure 2. RCS impeller.

The RCS employs the principle of air centrifugation, whereby the air is drawn in by the action of the impeller blades. The microbial particles present in the air are impacted onto the surface of the agar in the strip. The air flow is shown in Figure 3. The operating speed of the RCS is 4092 rpm and it draws 40 liters of air per minute. The flow rate remains constant by means of an electronic control which counts impulses reflecting from the rotating blades.

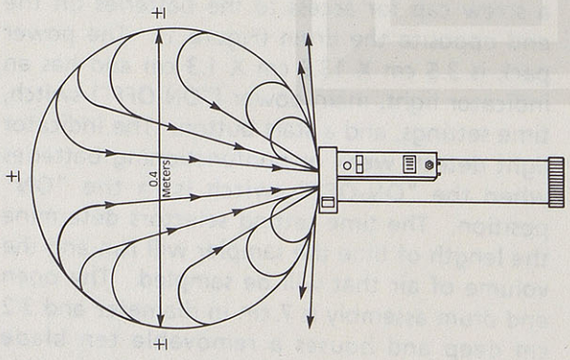


Figure 3. Air flow schematic.

Media Strips: Two types of agar strips were used. One contained nutrient agar for growth of bacteria. The other contained rose bengal agar for growth of fungi. Except for the agar, the strips were identical.

The agar strip used in the centri fugal air sampler was specially designed to give a surface area of 34 cm^2 (2 rows of 17 wells measuring 1 cm^2). This design allowed the strip to bend without cracking the agar as it was inserted into the open end drum, and also aided in the counting of the colonies. The agar strip was 21.2 cm X 2.5 cm X 0.3 cm and was packaged in a clear rigid plastic wrapper 23.5 cm X 3.2 cm X 0.9 cm with a seal on the cover (Figure 4). The agar strip was positioned in its wrapper so that the agar surface was facing away from the top of the wrapper. The agar strip may be stored at 4° C for at least three months or at room temperature for one month.

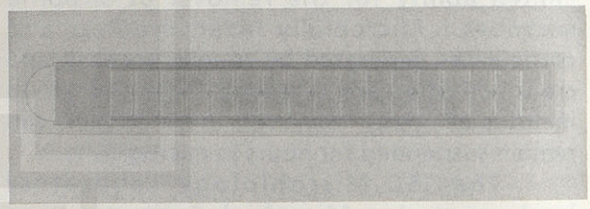


Figure 4. Agar strip.

Sample Procedures: The cabin air was monitored on both the middeck and flight deck. Samples were taken at the following times:

Preflight 24 hours before flight
Inflight #1 2nd day of mission
#2 mid-mission day
#3 next to last day
Postflight 6 hours after landing

The agar strips used inflight were stowed in the equipment area until postlanding destowage. The strips were packaged in wet ice and returned to the JSC Microbiology Laboratory where they were analyzed both quantitatively and qualitatively.

RESULTS

The results obtained from the microbial monitoring of the Orbiter air environment from STS missions 1-9 and mission 11 are given in Figures 5-8. Pre- and postflight sample analysis are shown for all the missions. Inflight sample analyses are shown for STS missions 6, 7, and 11. Inflight samples were also taken during another STS mission; however, the samples were compromised due to destowage and

transportation conditions. The agar strips were not destowed at the designated time and were subsequently exposed to temperatures incompatible with microbial recovery.

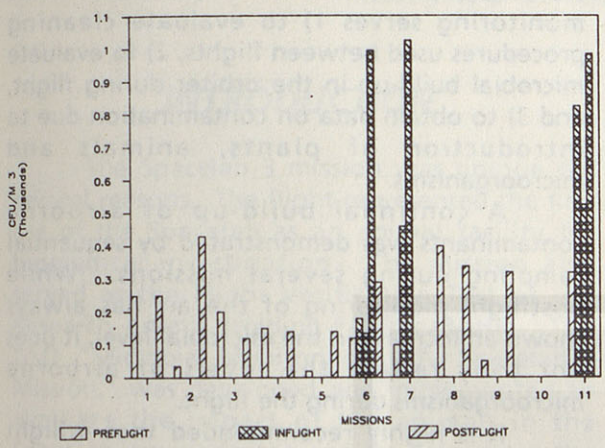


Figure 5. Airborne bacteria, mid deck.

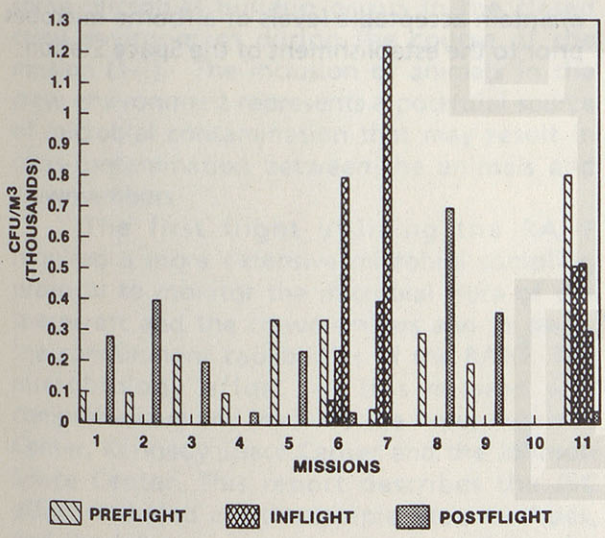


Figure 6. Airborne bacteria, flight deck.

Postflight microbial levels were generally 20-80% higher than preflight levels. However, the inflight measurements were more useful in evaluating the microbial levels of crew exposure during the mission. Four slight dropsin the microbial load were experienced during the first part of the mission, but this was followed by a rapid increase as the mission proceeded. The last inflight levels increased as much as 200-400 percent over the first inflight levels.

A qualitative analysis of each strip was also performed. This consisted of isolating and identifying each type of microorganism on the strip. A number of potential pathogens were isolated and are shown in Figure 9.

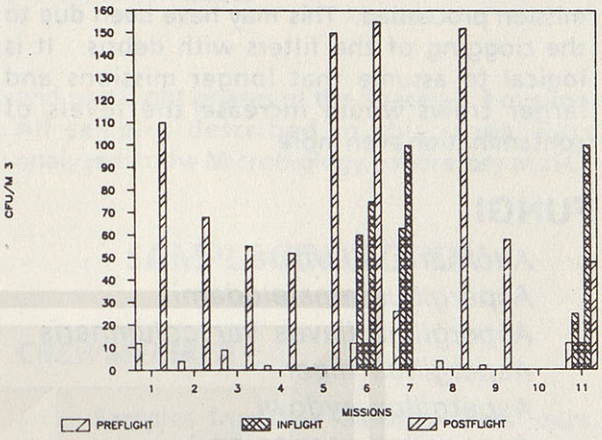


Figure 7. Airborne fungi, mid deck.

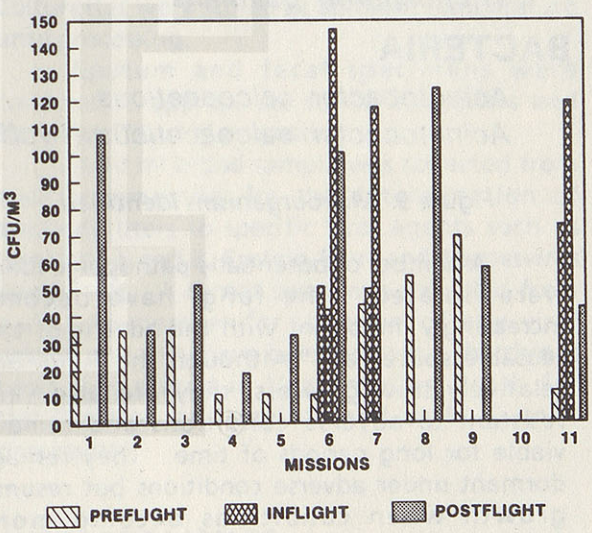


Figure 8. Airborne fungi, flight deck.

DISCUSSION

Inflight monitoring of the air proved to be a useful means of quantitating microbial changes that occurred during missions. A slight drop in the level of microorganisms in the air

was common during the early stages of the missions. This would indicate that the filtration system was adequate to clean the air at that time. However, as the mission progressed, the filtration system was no longer able to clear the air; the levels of contamination increased as the mission proceeded. This may have been due to the clogging of the filters with debris. It is logical to assume that longer missions and larger crews would increase the levels of contamination even more.

FUNGI

Alternaria alternata
Aspergillus amstelodami
Aspergillus flavus var columnaris
Aspergillus niger
Aspergillus sydowi
Aspergillus versicolor
Curvularia senegalensis
Drechslera hawaiiensis
Geotrichum candidum
Rhodotorula rubra
Trichosporon pullulans

BACTERIA

Acinetobacter calcoaceticus
Acinetobacter calcoaceticus (Iwoffi)

Figure 9. Microorganisms identified.

A number of potentially pathogenic fungi were isolated. The fungi have become increasingly important with the advent of the reusable spacecraft. Although the fungi are relatively slow growers, they are also very resistant to adverse conditions and remain viable for long periods of time. They remain dormant under adverse conditions but resume growth when conditions become more favorable. They pose a threat to the health of the crewmembers as 1) agents of infection, 2) allergens, and 3) producers of toxic metabolites. In addition, they are able to synthesize a vast array of enzymes enabling them to deteriorate practically every organic compound known.

CONCLUSIONS

The importance of the microbial monitoring of the air environment of the Shuttle missions, and eventually the Space Station, cannot be over emphasized. This monitoring serves 1) to evaluate cleaning procedures used between flights, 2) to evaluate microbial build-up in the orbiter during flight, and 3) to obtain data on contamination due to introduction of plants, animals and microorganisms.

A continual build-up of airborne contaminants was demonstrated by sequential sampling during several missions. While postflight monitoring of the air has always shown an increase in the microbial level, it does not truly reflect the levels of airborne microorganisms during the flight.

It is highly recommended that inflight monitoring of the airborne microbial contaminants be continued until a clear trend emerges. It is essential to evaluate the ability of the Orbiter's environmental control system to maintain acceptable levels of airborne microbes prior to the establishment of the Space Station.

MICROBIOLOGY REPORT IN SUPPORT OF THE SPACELAB 3 MISSION

Investigators: D. Pierson, Ph.D., and K. Gaiser

INTRODUCTION

The Spacelab 3 mission was unique for several reasons. The flight represented the first use of the Spacelab as an animal facility for biomedical investigation. The mission also served as the Flight Verification Test of the Research Animal Holding Facility (RAHF). The DSO, "Microbial Monitoring of the Spacelab 3 Mission," was developed and implemented to evaluate the impact of the animals in the Spacelab environment and to determine the ability of the RAHF to contain microorganisms.

Microbiological testing conducted on previous Space Shuttle flights has shown that some microbial buildup occurs in the closed crew environment during the course of the mission (1-2). The inclusion of animals in the crew environment represents a potential source of microbial contamination that may result in cross-contamination between the animals and crewmembers.

The first flight utilizing the RAHF required a more extensive microbial sampling protocol to monitor the microbial flora of the spacecraft and the crewmembers and to assess the containment capabilities of the RAHF. The microbiology effort for this mission was comprehensive and involved the Ames Research Center, Kennedy Space Center and the Johnson Space Center. This report describes the JSC effort. Included are the sample sites, methods, and the laboratory results obtained from the microbiological investigations conducted during the flight of Spacelab 3.

MATERIALS AND METHODS

SAMPLING PROTOCOL

Table 1 summarizes the sample sites, times, and types collected during the pre-, in-, and postflight phases of the Spacelab 3 mission. All samples described in this study were analyzed in the Microbiology Laboratory at JSC.

SAMPLE COLLECTION

CREWMEMBER

Samples from the crewmembers' ears, nose, throat, and hands were collected by the Culturette System during all sampling periods. With the exception of the throat cultures, all other samples were obtained after moistening the Culturette swab with 0.8 mM sterile phosphate buffer. After sampling, the Culturettes were stored at ambient temperature until processing.

Sputum and fecal specimens were collected in appropriate sterile containers and stored at 5° C until processing.

A 10 ml blood sample was collected from each crewmember for the determination of antibody titers to specific viral agents such as Hepatitis A and B, Epstein-Barr, and *Herpesvirus saimiri*, etc. A throat swab was collected from each crewmember for isolation of any viral agents that may have been present. The throat swab was placed in Veal Infusion Broth for stabilization and maintained at 5° C until processing.

SURFACE SAMPLES

Preflight and postflight surface samples from the Orbiter, Spacelab, and RAHF were collected using two sterile calcium alginate swabs moistened with 0.8 mM sterile phosphate buffer for each site. One swab was placed in trypticase soy broth for bacterial analysis; the other swab was placed in yeast malt broth for fungal analysis. All swabs were stabilized at 5° C until processing.

Inflight surface samples of the RAHF and crewmembers' gloves were collected using the Culturette system. One Culturette per site was used. The Culturette was moistened with 0.8 mM sterile phosphate buffer before sampling. The samples were stored at ambient temperature until processing.

AIR SAMPLES

Air samples were collected in the Orbiter, Spacelab, Life Sciences Support Facilities (LSSF), and the JSC and KSC Crew Quarters using a Reuter Centrifugal Air Sampler. Two strips were taken at each site. One strip contained trypticase soy agar for bacterial analysis and the other contained rose bengal agar for fungal analysis. Additionally, particulate samples were taken inflight using the same air sampler with a modified Biotest sampling strip. All samples were maintained at ambient temperature until processing. Particulates were enumerated by light microscopy and further analyzed by scanning electron microscopy.

ANIMAL FECAL SAMPLES

Fecal samples were collected at the LSSF from the rats and squirrel monkeys. Samples were stabilized at 5° C and delivered to JSC for processing.

SAMPLE PROCESSING AND ANALYSIS

Specific details of sample processing and analysis techniques for all types of samples collected are outlined in Spacelab 3 Microbial Contamination Control Plan In Support of DSO 0437.

RESULTS

CREWMEMBERS

PREFLIGHT

As part of the routine F-10 preflight physical exam, samples were collected from the ears, nose, and throat of each crewmember. In addition to the routine samples, fecal and serum samples were collected from each crewmember. The fecal samples were analyzed for the presence of ova and parasites and pathogenic bacteria and fungi. The serum sample was assayed for antibody titers to specific viral agents. A sputum sample was received from one crewmember. Additional throat cultures were taken at F-0 on all crewmembers.

There were no microorganisms of medical concern recovered preflight from any of the crewmembers' specimens (Tables 2-5). The predominant microbial genus recovered immediately preflight from the throat cultures in six of the seven crewmembers was *Streptococcus.*

Air samples were taken preflight at F-30 (KSC) and F-10 (JSC) to assess the microbial load in the Crew Quarters prior to crew occupancy of these facilities. Overall, the microbial levels obtained at KSC (Table 6) and JSC (Table 7) were consistent with those observed from preflight sampling for previous missions. Three types of potentially pathogenic fungi were isolated from the Crew Quarters (Tables 6 and 8). These organisms are common fungal atmospheric contaminants, and no action was taken.

INFLIGHT

Throat and hand cultures were collected from selected crewmembers on MD1, MD2, MD4, and MD6. Table 9 shows the microorganisms recovered from the inflight throat samples. With the exception of the *Bacillus* sp. and *Saccharomyces cerevisiae*, all other microorganisms were isolated from the crewmembers preflight throat samples. Neither of these microbial species are considered to be fecal contaminants or of probable animal origin.

Table 10 illustrates the microorganisms isolated from the hand swab samples. In some cases, samples were collected after the hands had been cleaned with alcohol wipes. This sampling method may explain the apparent lack of growth in some of the cultures. The only microorganism of interest was *Streptococcus faecalis* which was isolated on MD2 from the hands of crewmember 7. This microorganism was recovered from preflight rat and squirrel monkey fecal samples collected at F-30. This species is also a common isolate of human feces. A waste tray changeout occurred immediately preceding the hand sampling procedure and may have been the source of the microbe. This microorganism was not isolated at any later time from any crewmembers' hands.

POSTFLIGHT

Ear, nose, throat, and sputum cultures were collected at L+O and again at L+3 with the exception of the sputum samples. Microflora recovered from these samples was similar to preflight findings. Postflight samples do not indicate any cross-contamination between the animals and the crewmembers. *Pseudomonas aeruginosa, Pseudomonas fluorescens* (Table 2) and *Penicillium sp.* (Table 3) were isolated at L+3 and are not considered to be of flight origin.

SPACECRAFT

PREFLIGHT

Orbiter

Surface swabs were collected at F-30 after alcohol cleaning and again at F-0 just prior to crew entry. Analysis of these samples did not demonstrate any unusual microbial levels (Table 11). However, a small number of samples collected from the Waste Management System (WMS) at F-0 showed very high levels of non-pathogens. This was attributed to improper temperature control of the samples prior to processing at JSC. The microorganisms of significance are listed in Table 12.

Bacterial and fungal air samples were collected at F-30 and F-0 for baseline data (Figs. 1, 2). The microbial levels were approximately

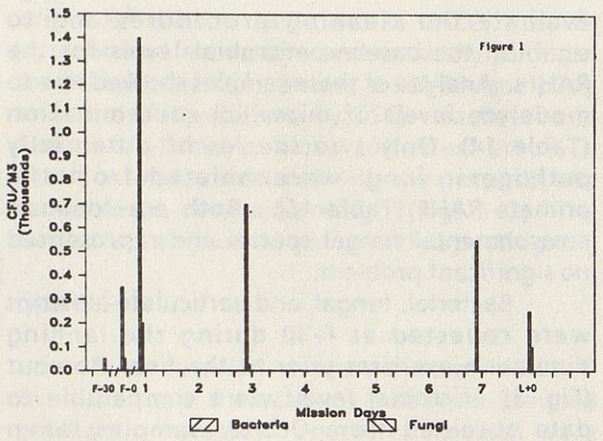


Figure 1. Bacterial and fungal counts, mid deck.

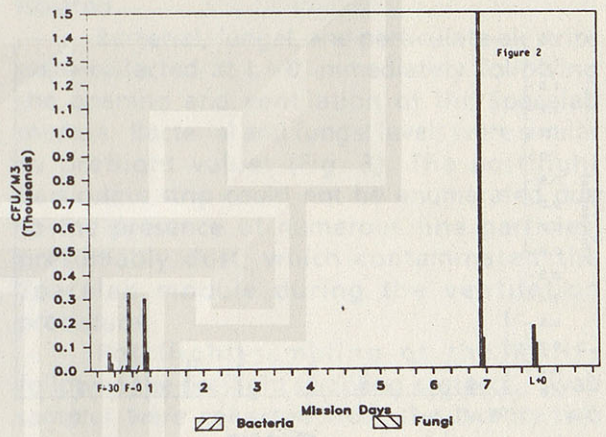


Figure 2. Bacterial and fungal counts, flight deck.

the same as seen in preflight sampling periods from previous missions. The particulate strips were not collected preflight.

Spacelab

Surface swabs were collected from six locations in the Spacelab module at F-30 after the wipedown and during the landing simulation exercises. The module was closed out upon completion of the exercises. No bacteria were isolated from any of the sites. Only 10 fungal colonies were recovered from the workbench handrail and were not of medical or epidemiological interest (Table 13).

A duplicate set of surface swabs was collected from twenty-two locations on the interior and exterior surfaces of the primate and rodent RAHFs. These samples were collected to

evaluate the cleaning procedures and to establish the baseline microbial levels for the RAHFs. Analysis of these samples showed low to moderate levels of microbial contamination (Table 14). Only two species of potentially pathogenic fungi were isolated from the primate RAHF (Table 15). Both are common environmental fungal species and represented no significant problem.

Bacterial, fungal, and particulate air strips were collected at F-30 during the landing simulation exercises prior to the final closeout (Fig. 3). Microbial levels were comparable to data obtained from Orbiter samples taken during previous missions. The particulate strips were not stored properly and, consequently, could not be processed.

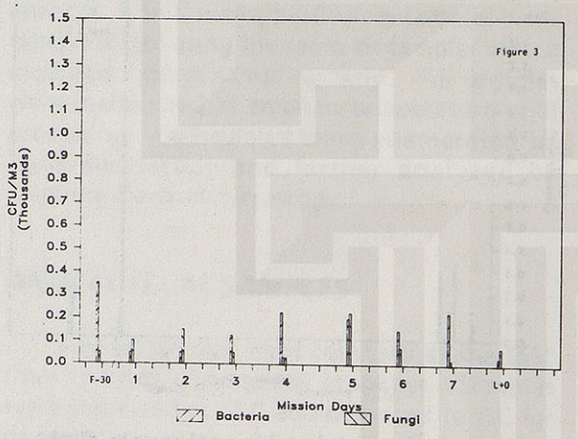


Figure 3. Bacterial and fungal counts, Spacelab.

INFLIGHT

Orbiter

No surface samples were collected from the Orbiter inflight. Bacterial, fungal, and particulate air sampling strips were collected on MD1, MD3, and MD7 on both the Mid Deck and the Flight Deck. Figures 1 through 3 illustrate the quantitation of the microorganisms and particulates recovered at each sampling period. Bacterial levels were markedly elevated on the Mid Deck on MD1 and decreased steadily throughout the mission (Fig. 1). Conversely, bacteria on the Flight Deck increased tenfold during the course of the flight (Fig. 2). No significant changes were observed in fungal levels during the flight. The majority of potential pathogens were fungi of the *Aspergillus* genus. *Staphylococcus aureus* was the only pathogenic bacterial species isolated (Table 17). No microorganisms of probable animal origin were isolated from the Orbiter inflight samples. Particulates on the Mid Deck decreased during the flight (only 2 samples) in much the same manner as the bacterial levels (Fig. 4). However, Flight Deck particulate values were high throughout the mission (Fig. 5). The elevated values for bacteria and particulates on the Flight Deck may be a result of the directional airflow from the Spacelab to the Flight Deck.

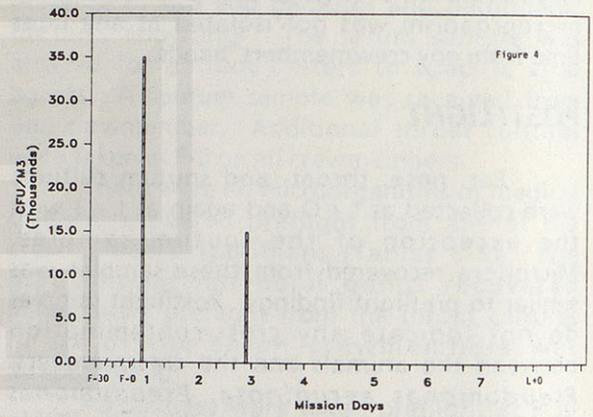


Figure 4. Particle counts, mid deck.

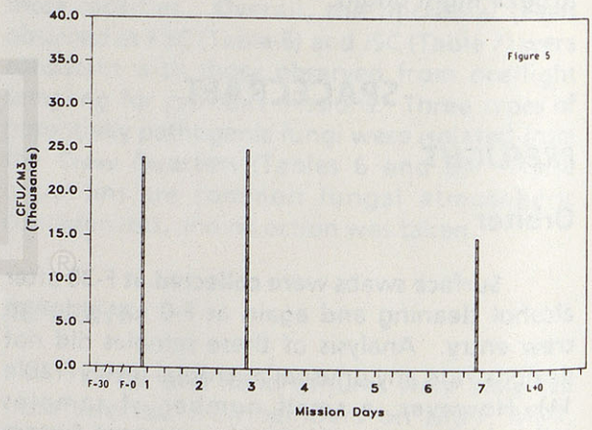


Figure 5. Particle counts, flight deck.

Spacelab

No samples from the Spacelab surfaces were collected inflight. Air samples were collected daily in conjunction with the waste tray changeout procedure. Bacterial, fungal, and particulate levels remained nearly constant

throughout the flight. An increase in particulate counts was noted during and following the waste tray changeout on MD4 (Fig. 6). *Aspergillus* sp. was the only potentially pathogenic microorganism isolated during the inflight sampling period (Table 16).

Five swab samples from the rodent RAHF and two swab samples from the primate RAHF were taken immediately following waste tray changeout on MD2, MD4, and MD6. All sample sites were external surfaces of the RAHFs. Additional samples were taken from crewmembers' gloves. Table 17 lists the microorganisms isolated from these sites. No fecal coliforms, indicative of fecal contamination, were isolated.

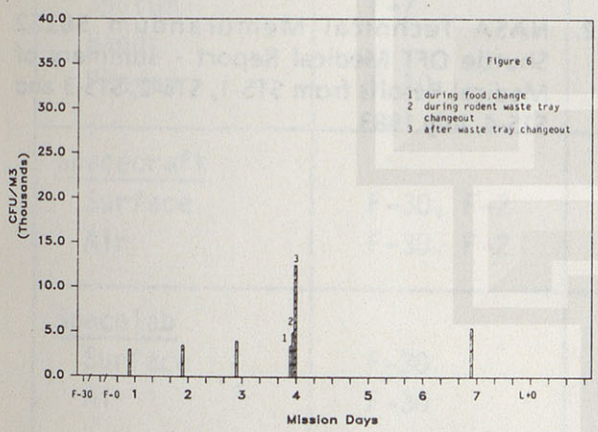


Figure 6. Particle counts, Spacelab.

POSTFLIGHT

Orbiter

Bacterial and fungal swab samples were collected at L + 0 at twenty-one sample sites. An approximate ten-fold increase from the preflight counts was seen in the number of bacteria in 11 of the 22 sites (Table 11). The number of fungal organisms did not increase significantly during the mission. Only two microbial species of interest, *Escherichia coli* and *Klebsiella pneumoniae*, were detected. *E. coli*, a fecal contaminant, was recovered from the air inlet ring and the slide valve which are two interior components of the Orbiter Waste Management System. This microbial species has been routinely recovered from these sites on previous flights. *K. pneumoniae* was isolated from the air return of the Aft Flight Deck. The origin of this contaminant is uncertain; *K. pneumoniae* was isolated immediately preflight from flight squirrel monkey #384-80 (sampling and analysis conducted by KSC). Bacterial and fungal air samples were collected at L + O. Postflight data correlates with the bacterial and fungal levels observed preflight (Figs. 1, 2). The particulate strips were not collected postflight.

Spacelab

Surface swabs were collected at L + O from the same six locations that were sampled preflight. Increases in bacterial growth were observed on five of the six locations (Table 13). No fungal growth was detected. *Staphylococcus aureus* was the only potential pathogen isolated.

Bacterial, fungal, and particulate air strips were collected at L + 0 immediately following the opening and ventilation of the Spacelab module. Bacterial and fungal levels were similar to preflight values (Fig. 3). The postflight particulate strip could not be enumerated due to the presence of numerous fine particles, presumably dust, which contaminated the Spacelab module during the ventilation procedure.

Postflight sampling of the RAHFs followed the preflight sampling protocol. Swab samples were collected from the twenty-two sites taken preflight. These samples were taken immediately after animal cage removal. A slight overall increase in bacterial growth was observed in samples from L + O (Table 14). The only organisms of significance were the fecal markers, *E. coli* and *S. faecalis*, and *Staphylococcus aureus*. All three species were isolated only from interior RAHF surface samples (Table 15). No appreciable change was observed in the number of fungal organisms.

ANIMAL MONITORING

At F-30 fecal samples were taken from selected rats and squirrel monkeys. Air samples were collected from the KSC LSSF during the same sampling period.

Table 18 lists all the microorganisms recovered from rat fecal samples. No microorganisms on the exclusion lists (Table 20 and 21) as defined by the JSC Human Research

Policy & Procedures Committee were isolated. Table 19 lists all the microorganisms recovered from the squirrel monkey fecal samples. Only one species on the exclusion list, *K. pneumoniae*, was isolated from monkey #3495. This animal was not selected for flight. However, immediately preflight *K. pneumoniae* was cultured from flight squirrel monkey #384-80 (sampling and analysis conducted by KSC-designated laboratories).

The air sample data collected from LSSF is shown in Table 22. The microbial levels were low and consistent with previous sampling data. Only common fungal environmental contaminants were isolated.

DISCUSSION

A total of 175 preflight, 81 inflight, and 98 postflight samples (354 total) were collected for quantitation and identification of the microbial flora present in the crew environment during the Spacelab 3 mission. The sampling protocol included samples from the air, various environmental surfaces, animals, and crewmembers.

Crewmember reports clearly documented the RAHF containment problems experienced during the flight. Comprehensive microbiological testing of the crewmembers and their environment during the SL-3 mission revealed no unusual microbial accumulations during the course of the mission. Levels of airborne microorganisms in the Spacelab were low compared to values obtained from the Orbiter during previous missions.

Fecal microorganisms, such as *E. coli* and *S. faecalis* were used as marker microorganisms for indication of fecal contamination. *E. coli* was detected only in the Orbiter Waste Management System and was probably of crew origin. *E. coli* and *S. faecalis* were also isolated from the interior surfaces of the RAHF postflight. In only two instances were microbial species of possible animal origin isolated external to the RAHF. *S. faecalis*, a fecal marker organism, was isolated on mission day 2 from a crewmember's hand immediately following waste tray changeout. *K. pneumoniae* was isolated postflight from an air return screen on the Orbiter Flight Deck. Unequivocal determination of origin, crewmember or experimental animal, was not possible.

The anomalies experienced during the SL-3 mission clearly demonstrated the value for redundancy in issues pertaining to the health of the crew. The use of Specific Pathogen Free animals (SPF) assured the safety of the crew when the RAHFs' containment system malfunctioned. It is strongly recommended that strict adherence to the SPF list be followed for all flights utilizing any biological specimens.

REFERENCES

1. NASA Technical Memorandum 58240 STS-1 Medical Report, December 1981.

2. NASA Technical Memorandum 58252 Shuttle OFT Medical Report - Summary of Medical Results from STS-1, STS-2, STS-3 and STS-4, July 1983.

Table 1. Microbial Samples Collected

Sample Sites	Sampling Times[a]		
	Preflight	Inflight	Postflight
Crew			
Ear	F-10		L+0, L+3
Nose	F-10		L+0, L+3
Throat	F-10, F-0	MD1, MD2, MD4, MD6	L+0, L+3
Feces	F-10		
Sputum	F-7		L+0
Hands		MD1, MD2, MD4, MD6	
Plasma	F-10		L+60
Spacecraft			
Surface	F-30, F-2		L+0
Air	F-30, F-2	MD1, MD7	L+0
Spacelab			
Surface	F-30		L+0
Air	F-30	MD2, MD3, MD4, MD5, MD6	L+0
RAHF			
Surface	F-30	MD2, MD6	L+0
Crew Quarters			
KSC	F-30		
JSC	F-10		
LSSF			
Air	F-30		
Animals			
Feces	F-30		

[a]F refers to days prior to flight, e.g., F-10 is 10 days preflight
L refers to days after landing, e.g., L+3 is 3 days post landing
MD refers to mission day

Table 2. Medically Important Microorganisms Isolated From Crewmember's Throat

CREWMEMBER	Preflight														Postflight													
	F-10							F-0							L+0							L+3						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
BACTERIA																										NS		
Acinetobacter calcoaticus bio anitratus	X																											
Branhamella catarrhalis													X													X		
Citrobacter sp.																												
Corynebacterium sp.		X		X	X			X		X				PO			PO	PO		PO	PO			PO	PO			PO
Enterobacter aerogenes																												X
Enterobacter cloacae																						X						
Haemophilus aphrophilus											X																	
Haemophilus sp. not influenzae								X					X	X						X				X	X			
Haemophilus parahaemolyticus		X					X																					
Haemophilus parainfluenzae	X	X	X	X	X	X	X		X			X			X	X						X	X			X		
Haemophilus parainfluenzae Biotype I																	X	X	X	X								
Haemophilus parainfluenzae Biotype II												X									X							
Haemophilus parainfluenzae Biotype III																												X
Kluyvera sp.												X																
Micrococcus sp.			X	X	X	X		X	X			X			X	X				X								
Neisseria sp.	X	X	X	X	X	X	X		X			X			X	X			X	X	X	X	X			X		X
Neisseria lactamicus																									X			
Pseudomonas aeroginosa																							X					
Pseudomonas fluorescens																						X						
Serratia rubidaea												X																
Staphylococcus aureus		X	X			X		X		X				X		X					X	X	X					
Staphylococcus epidermidis						X	X										X	X						X				X
Alpha-hemolytic Streptococcus	X	PO	PO	PO	PO	X	PO	PO	X	X	X	PO	PO	X	PO	X			PO		X					PO		
Gamma-hemolytic Streptococcus	PO	X	X	X	X	PO	X	X	PO			X			X				X					X	X	X		
Streptococcus equinus																							X					
Streptococcus morbillorium																	X											
Streptococcus mitis																						PO	PO					
Streptococcus pneumoniae									PO																			
Streptococcus salivarius											PO		X	X		PO												
Streptococcus sanguis																						X						
FUNGI																												
Aspergillus flavus group																			X									
Candida albicans			X						X	X							X									X		
Candida pseudotropicalis							X																					
Candida tropicalis													X															
Rhodotorula rubra		X																										

PO = Predominant organism
NS = No sample taken

Table 3. Medically Important Microorganisms Isolated From Crewmembers' Nose

	Preflight							Postflight														
	F-10							L+0							L+3							
CREWMEMBER	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	
BACTERIA																				NS		
Citrobacter sp.											PO								X			
Corynebacterium sp.	PO	X	X	PO	PO		X	PO	X			PO					X	X	PO			
Enterobacter aerogenes	X						X									X					X	
Enterobacter cloacae															X							
Micrococcus sp.				X																		
Proteus mirabilis		X														X						
Staphylococcus aureus	X	PO	X			PO		X	PO	PO	X		PO		PO	PO	PO					
Staphylococcus epidermidis	X	X	PO	X	X	X	PO	X	X	X	X	X	X	PO	X	X	X	PO	X		PO	
FUNGI																						
Candida albicans															X							
Penicillium sp. 1												X							X			
Penicillium sp. 2												X										
Scopulariopsis brevicaulis						X																

PO = Predominant organism
NS = No sample taken

Table 4. Medically Important Microorganisms Isolated From Crewmembers' Ears

	Preflight							Postflight														
	F-10							L+0							L+3							
CREWMEMBER	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	
BACTERIA																				NS		
Bacillus sp.		X						X														
Corynebacterium sp.				PO	PO	X						X			PO	PO	X	X	PO			
Enterobacter aerogenes	X																					
Enterobacter cloacae															X							
Lactobacillus sp.									X													
Micrococcus sp.	PO	X	PO		X	X	X	X	X		X											
Staphylococcus sp.																						
Staphylococcus aureus													PO	PO								
Staphylococcus epidermidis		PO	X	X	X	PO	PO	PO	PO	PO	PO	PO	X	X	X	X	PO	PO	X		PO	
FUNGI																						
Aspergillus sp.		X							X													
Candida parapsilosis		X																				
Fusarium sp.					X																	
Penicillium sp.																X		X				

PO = Predominant organism
NS = No sample taken

Table 5. Microbiological Analysis of Sputum from Crewmembers

CREWMEMBER	MICROORGANISMS	
	PREFLIGHT	POSTFLIGHT
1	NS	Alpha-hemolytic Streptococcus (PO) Neisseria sp. Gamma-hemolytic Streptococcus Corynebacterium sp. Micrococcus sp. Haemophilus sp. not influenza Candida albicans
2	NS	Alpha-hemolytic Streptococcus (PO) Neisseria sp. Gamma-hemolytic Streptococcus Staphylococcus aureus Staphylococcus epidermidis
5	Alpha-hemolytic Streptococcus (PO) Gamma-hemolytic Streptococcus Neisseria sp. Corynebacterium sp. Haemophilus sp. not influenzae	Alpha-hemolytic Streptococcus (PO) Neisseria sp. Gamma-hemolytic Streptococcus Micrococcus sp.
6	NS	Corynebacterium sp. (PO) Micrococcus sp. Haemophilus sp. not influenza Candida albicans
7	NS	Corynebacterium sp. (PO) Haemophilus parainfluenzae,- Biotype II Staphylococcus epidermidis

NS = No samples taken

Table 6. Quantitation of Airborne Microorganisms in the Kennedy Space Center (KSC) Crew Quarters at F-30

AREA	CFU/m^3 OF AIR[a]		POTENTIAL PATHOGEN
	BACTERIA	FUNGI	
BEDROOM 1B	38	438	
BEDROOM 2B	50	238	
BEDROOM 3B	50	363	
BATHROOM B	100	175	
BEDROOM 1C	138	100	
BEDROOM 2C	38	113	Drechslera hawaiiensis
BEDROOM 3C	75	163	
BATHROOM A	88	88	
GYM	50	75	
DINING ROOM	12	88	
LIVING ROOM	38	50	
KITCHEN	12	188	
CONFERENCE ROOM	12	150	
LIVING ROOM A	0	50	

[a]Colony forming units per cubic meter of air

Table 7. Quantitation of Air Borne Microorganisms Isolated from the Johnson Space Center (JSC) Crew Quarters at F-10

TRAILER #	LOCATION	CFU/m^3 of Air	
		BACTERIA	FUNGI
1	Bedroom #1	1000	3500
	Bathroom	2050	3750
	Kitchen	500	1500
	Living Room	300	1200
	Bedroom #2	50	400
	Hall	550	900
	Bedroom #3	100	200
	Bedroom #4	150	750
2	Bedroom #1	500	1350
	Bathroom #1	600	1600
	Kitchen	150	800
	Living Room	500	1250
	Bedroom #2	150	200
	Hall	200	500
	Bathroom #2	150	300
	Bedroom #3	50	250
Outside Trailer	Bathroom	450	600
	Area between Trailer 1&2	50	300
3	Food Storage Room	300	200
	Bathroom	200	1250
	Hall	300	500
	Living Room	650	1400
	Dining Room	800	600
	Kitchen	150	950
4	Bedroom #1	550	1850
	Bathroom #1	800	2150
	Kitchen	300	1300
	Living Room	700	1750
	Bedroom #2	500	400
	Hall	0	550
	Bathroom #2	150	950
	Bedroom #3	900	450

Table 8. Potential Pathogens Isolated from Johnson Space Center (JSC) Crew Quarters at F-10

Potential Pathogen	Location
Aspergillus sp.	Trailer 1, Bedroom #2 Trailer 2, Bedroom #2 Trailer 2, Hall Trailer 3, Bathroom Trailer 4, Kitchen Trailer 4, Bathroom #2
Aspergillus flavus	Trailer 1, Living Room Trailer 1, Hall
Drechslera hawaiiensis	Trailer 1, Bedroom #1 Trailer 1, Bathroom #1 Trailer 1, Bedroom #2 Trailer 2, Bedroom #1 Trailer 2, Bathroom #1 Bathroom between Trailers 1 & 2 Trailer 4, Bedroom 1

Table 9. Medically Important Microorganisms Isolated From Crewmembers' Throat (Inflight)

CREWMEMBER	Inflight																									
	MD1							MD2							MD4							MD6						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
BACTERIA	NS	NS	NS	NS			NS	NS	NS	NS		NS	NS		NS	NS												
Bacillus sp.											PO																	
Corynebacterium sp.					X	PO								X				PO	PO									
Haemophilus sp. not influenzae																						X	X	X		X	X	
Micrococcus sp.					X																			X				
Neisseria sp.																						X	X	X	X	X		X
Staphylococcus aureus																							X		X			
Staphylococcus epidermidis					PO						X			PO				PO	X	X	PO	X	X	X	X	X	X	X
Alpha hemolytic Streptococcus											X											PO	PO	PO	X	PO	X	PO
Gamma hemolytic Streptococcus						X												X				X	X	X	PO		PO	
Streptococcus salivarius																					PO							
FUNGI																												
Aspergillus flavus group																												X
Candida albicans					X									X			X		X		X			X	X	X		X
Saccharomyces cerevisiae						X														X							X	

PO = Predominant organism
NS = No sample taken

Table 10. Medically Important Microorganisms Isolated from Crewmembers' Hands (Inflight)

Crewmember	MD1	MD2	MD4	MD6
3	NS	No growth	Aspergillus flavus group	Staphylococcus epidermidis
4	NS	No growth	Aspergillus flavus group	Staphylococcus epidermidis
5	No growth	NS	No growth	Aspergillus flavus group Cryptococcus albidus var albidus
6	NS	Aspergillus flavus group	Aspergillus flavus group	Penicillium sp.
7	NS	Streptococcus faecalis	No growth	No growth

NS = No samples taken

Table 11. Quantitation of Microorganisms Isolated from Orbiter Surface

SAMPLE SITE	SAMPLE PERIOD[a]					
	Bacterial			Fungal		
	F-30	F-0	L+0	F-30	F-0	L+0
Urine collection device	$1.5X10^1$	$2.4X10^3$[b]	$3.8X10^2$	0	0	0
Air Inlet Ring	$1.5X10^1$	$1.0X10^4$[b]	$1.0X10^3$	0	$1.0X10^1$	0
Slide valve	$5.2X10^2$	$2.4X10^4$[b]	$1.3X10^3$	0	0	$1.0X10^1$
WCS handle	$7.5X10^0$	$4.9X10^2$[b]	$2.3X10^2$	0	$2.1X10^1$	$1.0X10^1$
WMS Trash Bag (MF43H)	NS	$2.0X10^4$[b]	$4.1X10^2$	NS	$1.0X10^1$	0
Air supply vent, Mid Deck	$4.5X10^1$	$1.7X10^4$[b]	$7.7X10^2$	$5.0X10^0$	$6.3X10^1$	$9.4X10^1$
Wall above hatch	$2.3X10^1$	$4.5X10^1$	$7.5X10^1$	0	0	0
Water dispenser needle	0	$9.0X10^0$	$3.8X10^1$	0	0	$6.3X10^1$
Personal hygiene nozzle	$3.0X10^1$	$9.0X10^0$	NS	$1.5X10^1$	0	NS
Food locker (MF14E)	NS	0	$5.3X10^2$	NS	0	0
Food trays (MF23H)	NS	$9.0X10^0$	$1.2X10^2$	NS	0	$1.0X10^1$
Food warmer (MF23H)	0	$9.0X10^0$	$3.0X10^1$	0	0	$1.0X10^1$
Sleep restraint (2)	NS	$9.0X10^0$	$1.1X10^2$	NS	0	$1.2X10^2$
Air supply vent, sleep station	$1.1X10^2$	$9.0X10^0$	$9.6X10^1$	$3.5X10^1$	$1.0X10^1$	$3.2X10^1$
Wet trash	$2.3X10^2$	$7.5X10^1$	$8.3X10^1$	0	$1.0X10^1$	0
CO_2 Absorber (B) latch handle	NS	0	NS	NS	0	NS
Window 8 gasket	$1.7X10^2$	$3.8X10^1$	$4.9X10^2$	$5.0X10^0$	0	0
Air supply vent, flight deck	$1.5X10^1$	$9.0X10^0$	$3.8X10^2$	$2.0X10^1$	$1.0X10^1$	$1.0X10^1$
Control stick, Commander	$2.3X10^1$	$9.0X10^0$	$7.5X10^0$	0	0	0
Control stick, Pilot	$9.8X10^1$	$9.0X10^0$	$2.9X10^2$	0	0	0
Data file case	$7.5X10^1$	$9.0X10^0$	$1.4X10^2$	$5.0X10^0$	0	0
Air return, Aft flight deck	NS	$9.0X10^0$	$1.2X10^3$	NS	$3.0X10^2$	$2.1X10^2$

[a]Quantitation given in colony forming units per cm^2
[b]Sample not refrigerated after collection
NS=No Sample taken

Table 12. Potential Pathogens Isolated from Orbiter Surface - STS 51-B

SAMPLE PERIOD	POTENTIAL PATHOGENS	ORBITER LOCATION
F-30	*ASPERGILLUS* SP.	AIR SUPPLY VENT - SLEEP STATION
	ASPERGILLUS FLAVUS	AIR SUPPLY VENT - FLIGHT DECK
	CURVULARIA LUNATA	AIR SUPPLY VENT - SLEEP STATION
	PENICILLIUM SP.	DATA FILE CASE
		AIR SUPPLY VENT - SLEEP STATION
F-0	*ACINETOBACTER CALCOAETICUS*	WMS TRASH BAG (MF43H)
	ALTERNARIA SP.	WCS HANDLE
	ASPERGILLUS SP.	AIR SUPPLY VENT - MID DECK
		AIR SUPPLY VENT - FLIGHT DECK
		AIR RETURN - AFT FLIGHT DECK
	ASPERGILLUS FLAVUS	WET TRASH
	ASPERGILLUS NIGER GROUP	WCS HANDLE
	GRAM NEGATIVE ROD CDC GROUP VE-2	AIR SUPPLY VENT - MID DECK
	STAPHYLOCOCCUS AUREUS	WMS TRASH BAG (MF43H)
		AIR SUPLY VENT - MID DECK
		SLEEP RESTRAINTS
L+0	*ACREMONIUM* SP.	WCS HANDLE
	ASPERGILLUS SP.	AIR SUPPLY VENT - SLEEP STATION
	ASPERGILLUS NIGER GROUP	AIR RETURN - AFT FLIGHT DECK (2 SPECIES)
	ENTEROBACTER AEROGENES	AIR SUPPLY VENT - MID DECK
	ESCHERICHIA COLI	WATER DISPENSER NEEDLE
	KLEBSIELLA PNEUMONIAE PENICILLIUM SP.	SLEEP RESTRAINT (2)
	STAPHYLOCOCCUS AUREUS	WINDOW 8 GASKET
		AIR RETURN - AFT FLIGHT DECK
		AIR INLET RING - WMS
		SLIDE VALVE - WMS
		AIR RETURN - AFT FLIGHT DECK SLIDE VALUE
		AIR RETURN - AFT FLIGHT DECK
		FOOD TRAYS (MF23H)

Table 13. Quantitation of Microorganisms Isolated from the Spacelab Surface

Sample Site	Sample Period[a]			
	Bacterial		Fungal	
	F-30	L+0	F-30	L+0
Air Vent	0	$9.0x10^{0}$[b]	0	0
Workbench Handrail	0	$5.3x10^{1}$	$1.0x10^{1}$[c]	0
Utility Box Latch	0	$4.0x10^{1}$	0	0
CO_2 Absorber Latch	0	$3.0x10^{1}$	0	0
Workbench Surface - Center	0	0	0	0
Trash Container (2 loops)	0	$1.4x10^{2}$	0	0

[a]Quantitation in colony forming units/cm^2
[b]Potential pathogen Staphylococcus aureus, isolated
[c]Potential pathogen Penicillium sp., isolated

Table 14. Quantitation of Microorganisms Isolated from the RAHF Surface

Sample Site	Sample Period[a]					
	Bacterial			Fungal		
	F-30A	F-30B	L+0	F-30A	F-30B	L+0
Primate RAHF						
Quick disconnect, lixit, slot 1	$1.0x10^{2}$	0	0	0	0	0
Inner door, inner surface slot 1	0	$7.5x10^{1}$	$1.9x10^{2}$	0	0	0
Quick disconnect, lixit, slot 2	0	0	0	$2.0x10^{1}$	0	0
Inner door, inner surface, slot 3	$1.0x10^{2}$	0	$8.3x10^{1}$	0	0	0
Case air inlet plenum, slot 2	0	0	$2.4x10^{3}$	0	0	0
Case air outlet plenum, slot 2	0	$7.5x10^{1}$	$9.8x10^{1}$	0	0	0
Outer door, outer surface, slot 2	$1.0x10^{2}$	0	$9.0x10^{0}$	0	0	0
Outer door, outer surface, slot 4	0	$7.5x10^{1}$	0	0	0	0
Bleed air outlet port	0	0	$4.5x10^{2}$	$5.0x10^{0}$	0	$1.4x10^{2}$
Bleed air inlet port	$3.0x10^{1}$	0	$1.3x10^{5}$	0	0	0
Rodent RAHF						
Lixit, front, slot 4	$1.0x10^{2}$	0	$1.9x10^{2}$	0	0	0
Lixit, rear, slot 6	$2.1x10^{3}$	0	$2.5x10^{3}$	0	0	0
Inner door,inner surface, slot 6	0	0	0	0	0	0
Lixit, front, slot 8	0	0	$2.8x10^{3}$	0	0	0
Lixit, rear, slot 10	$2.3x10^{1}$	0	$9.0x10^{0}$	0	$5.0x10^{0}$	0
Case air inlet plenum, slot 10	0	0	$9.0x10^{0}$	0	$2.5x10^{1}$	0
Case air outlet plenum, slot 10	$1.4x10^{1}$	0	$9.0x10^{0}$	0	$5.0x10^{0}$	0
Inner door, inner surface, slot 10	0	$7.5x10^{1}$	$9.0x10^{0}$	0	0	0
Outer door, outer surface, slot 1	0	0	$9.0x10^{0}$	0	0	0
Outer door, outer surface, slot 3	$1.0x10^{2}$	0	0	0	0	0
Bleed air outlet port	$1.0x10^{2}$	0	0	0	0	0
Bleed air inlet port	$1.0x10^{2}$	$7.5x10^{1}$	$1.0x10^{3}$	$5.0x10^{0}$	0	0

[a]Quantitation given in colony forming units/cm^2

Table 15. Potential Pathogens Isolated from the Primate and Rodent Research Animal Holding Facilities (RAHF) During Pre- and Postflight

Sample Period	Potential Pathogens	RAHF Location
F-30	Aspergillus sp. Penicillium sp.	Bleed air outlet port - primate Quick disconnect, lixit, slot 2 - primate
L+0	Escherichia coli	Lixit, rear, slot 6 - rodent Lixit, front, slot 8 - rodent
	Penicillium sp.	Bleed air outlet port - primate
	Pseudomonas acidovorans	Inner door, inner surface, slot 3 - primate
	Staphylococcus aureus	Case air inlet plenum, slot 2 - primate Lixit, rear, slot 10 - rodent Bleed air inlet port - rodent
	Streptococcus faecalis	Inner door, inner surface, slot 1 - primate Lixit, rear, slot 6 - rodent Case air inlet plenum, slot 10 - rodent Case air outlet plenum, slot 10 - rodent Inner door, inner surface, slot 10 - rodent

Table 16. Potential Pathogens Isolated from Spacecraft Air

Sample Period	Potential Pathogens	Orbiter Location
F-30	None Isolated	
F-0	Aspergillus sp. (2) Aspergillus glaucus	Flight Deck
MD1	Aspergillus sp. Aspergillus flavus group	Mid Deck
MD2	Aspergillus flavus group	Spacelab
MD3	Aspergillus sp. Aspergillus flavus group	Spacelab
MD4	Aspergillus sp.	Spacelab
MD5	Aspergillus sp. Aspergillus flavus group	Spacelab
MD7	Aspergillus sp. Staphylococcus aureus	Spacelab Flight Deck
L+0	Aspergillus sp. (2)	Flight Deck

( ) number of species isolated

Table 17. Inflight Surface Samples

Rodent RAHF			
	MD2	MD4	MD6
Cage 1 3 5	No growth No growth No growth	No growth No growth Aspergillus flavus group	Aspergillus flavus group No growth Staphylococcus epidermidis
Outlet Port	No growth	No growth	Staphylococcus epidermidis, Gram-negative rod CDC VE-2
Slot 6/8	No growth	Aspergillus flavus group	Staphylococcus epidermidis Aspergillus flavus group

Primate RAHF			
	MD2	MD4	MD6
Cage 1 4	NS NS	NS NS	NS NS
Outlet Port	Aspergillus flavus group Dematiaceous fungus	Staphylococcus aureus	Staphylococcus epidermidis
Slot 1/2	Bacillus sp. Dematiaceous fungus	No growth	Bacillus sp.

Gloves			
	MD2	MD4	MD6
	Staphylococcus epidermidis, Micrococcus sp. Aspergillus flavus group	Staphylococcus epidermidis	Staphylococcus epidermidis
*MD5 - Gloves Aspergillus flavus group			

NS = No samples taken

Table 18. Microbiology and Parasitology Analysis of Rat Feces (F-30)

Rat ID Number	1	2	4	6	7	14	17	32	34	40	42	61	63	64	95	111	112
Bacteria																	
Citrobacter amalonaticus		X									X						
Enterobacter cloacae														X			
Escherichia coli	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Proteus mirabilis																X	
Streptococcus avium										X		X					
Streptococcus faecalis	X			X	X	X		X	X		X						
Fungi																	
Moniliaceous fungi (no conidia)													X				
Penicillium sp.	X							X	X	X		X		X			
Ova & Parasites																	
None Observed	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Table 19. Microbiology and Parasitology Analysis of Squirrel Monkey Feces (F-30)

Monkey ID Number	3165*	3483	3495	384-80*
Bacteria				
Escherichia coli		X	X	
Klebsiella pneumoniae			X	
Proteus mirabilis	X	X	X	X
Staphylococcus aureus	X			
Streptococcus faecalis			X	
Ova and Parasites				
None Observed	X	X	X	X

*Flight animals

Table 20. SPF Criteria for Rats

MICROORGANISM	CULTURE SITE/MATERIAL OR IDENTIFICATION TEST
BACTERIA:	
Streptobacillus Moniliformis	Oral
Spirillum Minor	Oral
Streptococcus Pneumoniae	Oral, Nasal
Streptococcus, Beta Hemolytic	Oral, Nasal
Pseudomonas Aeruginosa	Oral, Fecal
Salmonella sp.	Fecal
Leptospira sp.	Urine
Klebsiella Pneumoniae	Fecal, Oral, Nasal
Klebsiella Oxytoca	Fecal, Oral, Nasal
Campylobacter sp.	Fecal
VIRUSES:	
Lymphocytic Choriomeningitis Virus	Blood
Sendai Virus	Blood
FUNGI	
All Dermatophytes	Skin
ECTO PARASITES	Skin, Hair
ENDO PARASITES	Feces, Caecal Contents

Table 21. SPF Criteria for Squirrel Monkeys

MICROORGANISM	CULTURE SITE/MATERIAL OR IDENTIFICATION TEST
BACTERIA:	
Shigella sp.	Fecal
Salmonella sp.	Fecal
Streptococcus pneumoniae	Oral, Fecal
Klebsiella pneumoniae	Oral, Fecal
Mycobacterium tuberculosis	Skin Test, X-Ray
Pasteurella multocida	Nasal, Fecal
Campylobacter sp.	Fecal
Leptospira sp.	Urine
Streptococcus, Beta Hemolytic (Group A)	Oral, Nasal
VIRUSES:	
Lymphocytic choriomeningitis virus	Blood (Serology)
Herpesvirus tamarinus	Blood (Serology)
Herpesvirus saimiri	
ENDOPARASITES:	
Trichomonas	Oral
Acanthocephlans	Feces
Strongyloides	Feces
Entamoeba histolytica	Feces
Hemoprotozoa	Blood
FUNGI:	
All Dematophytes	Skin

Table 22. Quantitation of Airborne Microorganisms
Life Sciences Support Facility (LSSF) at F-30

Sample Site	CFU/m^3 of Air		
	Bacteria	Fungi	Potential Pathogens
Hall	0	$1.5X10^2$	*Aspergillus* sp. (3)
X-Ray	0	$1.1X10^2$	*Aspergillus* sp. (2)
Cental Supply	0	$8.8X10^1$	*Aspergillus flavus* *Aspergillus* sp. (3)
AHR 2	0	$7.5X10^1$	*Aspergillus* sp. (2)
AHR 5	0	$1.9X10^2$	*Aspergillus* sp.
AHR 6	0	$2.7X10^2$	*Aspergillus* sp. (4)
AHR 7	$1.5X10^2$	0	

( ) number of different species isolated.

Section Five
Space Motion Sickness

An understanding of vestibular and somatosensory roles in adaptation to microgravity may hold the key to prevention and treatment of Space Motion Sickness. This crewmember is using a device designed to measure ocular counterrolling in microgravity conditions. The neck brace is to "decouple" somatosensory receptors in the neck.

A CURRENT STATUS OF SMS EXPERIENCE IN SHUTTLE CREWMEMBERS

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INTRODUCTION

Space motion sickness (SMS) is a problem that has been associated with space travel for over twenty years and is the most clinically significant medical phenomenon during the first four days of spaceflight. Upon entry into micro-gravity, the body begins to adapt to this novel environment. The sensory-motor system, among others, must learn to function appropriately for the new conditions. Adaptation of the vestibular system and, more generally, the sensory-motor system is of particular importance in the development and resolution of symptoms of SMS.

Throughout the United States space program information concerning SMS has been collected by the NASA flight surgeons examining and debriefing the crewmembers postflight. Information collected during the Space Shuttle program makes up the substance of this paper.

INCIDENCE

During the United States manned spaceflight programs SMS has been reported by crewmembers during Apollo, Skylab, and Shuttle flights. The reason astronauts did not experience and report SMS symptoms during the Mercury and Gemini flights is felt to be largely due to the marked limitation of motion of the crewmembers in these small space capsules. As mobility increased in the larger Apollo, Skylab, and Shuttle spacecraft, susceptible crewmembers experienced one or more of the motion sickness symptoms listed in Table 1.

The incidence of SMS symptoms across the United States manned spaceflight programs, through the first 19 Shuttle flights, is given in Table 2. The percent incidence shown in Table 2 is total incidence for each program and includes cases of SMS ranging from mild through severe. As is shown, the incidence of SMS during the Shuttle flights has been 53 percent.

TABLE 1. SMS SYMPTOMS

HEADACHE	CENTRAL NERVOUS SYSTEM
MALAISE	
LETHARGY/APATHY	
DROWSINESS	
DISEQUILIBRIUM	
ANOREXIA	GASTRO-INTESTINAL SYSTEM
STOMACH AWARENESS	
NAUSEA	
VOMITING	

TABLE 2. SMS INCIDENCE

- MOST CLINICALLY SIGNIFICANT MEDICAL PHENOMENON DURING THE FIRST SEVERAL DAYS OF SPACEFLIGHT
- UNITED STATES INCIDENCE

MERCURY	0%
GEMINI	0%
APOLLO	35%
SKYLAB	60%
APOLLO-SOYUZ	0%
SHUTTLE	53%

This high incidence is of increased significance in the Shuttle program for two reasons. First, because Shuttle flights generally are only 5 to 7 days in duration, SMS symptoms are present during one-third to one-half of the flight and are a nuisance to crewmembers both in terms of personal comfort and in decreased work efficiency. Second, since the Shuttle is flown back to Earth like an airplane and requires crewmember control, an emergency requiring an early landing could result in a sick astronaut having to pilot the spacecraft.

CLINICAL CHARACTERISTICS

In order to apply a uniform assessment of SMS symptoms and severity across all Shuttle flights, a classification of symptom severity was developed by Homick and coworkers (1). Four categories of SMS severity were identified based on type, duration and severity of individual symptoms. Using information provided by the crewmembers during their medical debriefings after each mission, the interviewing flight surgeon assigned each crewmember into one of the four categories: none, mild, moderate, or severe space motion sickness. The description of each of these categories of SMS can be found in Table 3.

TABLE 3. SMS CATEGORIZATION

NONE (0):	NO SIGNS OR SYMPTOMS REPORTED WITH EXCEPTION OF MILD TRANSIENT HEADACHE OR MILD DECREASED APPETITE
MILD (1):	ONE TO SEVERAL SYMPTOMS OF A MILD NATURE; MAY BE TRANSIENT AND ONLY BROUGHT ON AS THE RESULT OF HEAD MOVEMENTS; NO OPERATIONAL IMPACT; MAY INCLUDE SINGLE EPISODE OF RETCHING OR VOMITING; ALL SYMPTOMS RESOLVED IN 36-48 HOURS
MODERATE (2):	SEVERAL SYMPTOMS OF A RELATIVELY PERSISTENT NATURE WHICH MAY WAX AND WANE; LOSS OF APPETITE; GENERAL MALAISE, LETHARGY AND EPIGASTRIC DISCOMFORT MAY BE MOST DOMINANT SYMPTOMS; INCLUDES NO MORE THAN TWO EPISODES OF VOMITING; MINIMAL OPERATIONAL IMPACT, ALL SYMPTOMS RESOLVED IN 72 HOURS
SEVERE (3):	SEVERAL SYMPTOMS OF A RELATIVELY PERSISTENT NATURE THAT MAY WAX AND WANE; IN ADDITION TO LOSS OF APPETITE AND STOMACH DISCOMFORT MALAISE AND/OR LETHARGY ARE PRONOUNCED; STRONG DESIRE NOT TO MOVE HEAD; INCLUDES MORE THAN TWO EPISODES OF VOMITING; SIGNIFICANT PERFORMANCE DECREMENT MAY BE APPARENT; SYMPTOMS MAY PERSIST BEYOND 72 HOURS

The first 19 Shuttle flights covered the period from April 1981 through August 1985. Seventy-one different individuals flew on these missions. With several individuals flying more than once, these people represent a total of 93 crewperson-flights. Symptoms of SMS were experienced by 49 of these 93 crewpersons for a total incidence of 53 percent. Twenty-four of the cases were mild, constituting 49 percent of the cases or 26 percent of the total; 18 were moderate in severity, making up 37 percent of the cases or 19 percent of the total; and 7 were judged to be severe cases, representing 14 percent of the cases or 8 percent of the total crewpersons flown. These data are summarized in Table 4.

TABLE 4. SMS EXPERIENCE ON FIRST 19 SHUTTLE FLIGHTS

STS-1 APRIL 1981 THROUGH STS-51-F AUGUST 1985	NUMBER	PERCENT OF CASES	PERCENT OF TOTAL
TOTAL CREWPERSONS	93		
TOTAL CASES OF SMS	49		53%
MILD	24	49%	26%
MODERATE	18	37%	19%
SEVERE	7	14%	8%

Each of the 49 cases of SMS was evaluated according to the specific symptoms experienced by each crewmember. The results are summarized in Table 5. The most commonly experienced symptoms, taking all cases, were loss of appetite (82 percent), vomiting (82 percent), stomach awareness (57 percent), malaise (57 percent), headache (53 percent), and lethargy (51 percent). Of interest is the fact that the incidence of nausea was only 45 percent compared to an 82 percent incidence of vomiting. Many of the crewmembers who vomited reported that they frequently had little, if any, nausea precedent to vomiting and if nausea was present it often began only a few seconds to minutes before frank vomiting occurred. Anorexia and vomiting were found in all of the individuals with moderate or severe SMS while only 63 percent of the crewmembers classified as mild cases had these symptoms. It is also interesting to note that, whereas 63 percent of the mild cases described anorexia and vomiting, only 38 percent experienced malaise. This apparent discrepancy is explained by the fact that a number of astronauts indicated that they felt quite well before and after vomiting and denied any sensation of malaise. They found that the vomiting was very sudden in onset without precedent nausea or malaise.

TABLE 5. INCIDENCE OF SYMPTOMS

	MILD (n = 24)	MODERATE (n = 18)	SEVERE (n = 7)	TOTAL (n = 49)
HEADACHE	12 (50%)	9 (50%)	5 (71%)	26 (53%)
MALAISE	9 (38%)	13 (72%)	6 (86%)	28 (57%)
LETHARGY	9 (38%)	11 (61%)	5 (71%)	25 (51%)
DROWSINESS	2 (8%)	6 (33%)	4 (57%)	12 (24%)
DISEQUILIBRIUM	3 (12%)	7 (39%)	1 (14%)	11 (22%)
ANOREXIA	15 (63%)	18 (100%)	7 (100%)	40 (82%)
STOMACH AWARENESS	12 (50%)	11 (61%)	5 (71%)	28 (57%)
NAUSEA	8 (33%)	9 (50%)	5 (71%)	22 (45%)
VOMITING	15 (63%)	18 (100%)	7 (100%)	40 (82%)

In addition to the specific symptoms, the time course of the symptoms was also of interest. The time of onset of symptoms, the time of peak intensity, and the time period in which the symptoms of SMS completely abated were obtained during the medical debriefing. Symptoms during the first 36 hours were grouped in 6-hour time blocks; symptoms occurring thereafter were grouped in 12-hour time blocks. The majority of susceptible crewmembers developed the onset of their symptoms during the first 6 hours of flight. The onset of symptoms has been seen from as early as 15 minutes after launch to as late as the end of the second day of a mission. The symptoms tend to reach peak intensity either near the middle of the first flight day or the middle of the second day. In the majority of cases the symptoms resolved by the end of the third day of the flight. Figure 1 shows the time course of onset, peak, and resolution of symptoms plotted against the mission elapsed time. The dip in the time of peak intensity at 18 to 24 hours most likely represents the abatement of symptoms during the first sleep period when the movements of crewmembers are minimized. When the time course of symptoms was plotted for each severity category, as is shown in Figures 2, 3, and 4, essentially the same patterns were seen as in the plot for the combined grouping, with the exception of the onset of symptoms. All the individuals who experienced symptoms of moderate or severe intensity had the onset of their symptoms within the first 6 hours of flight.

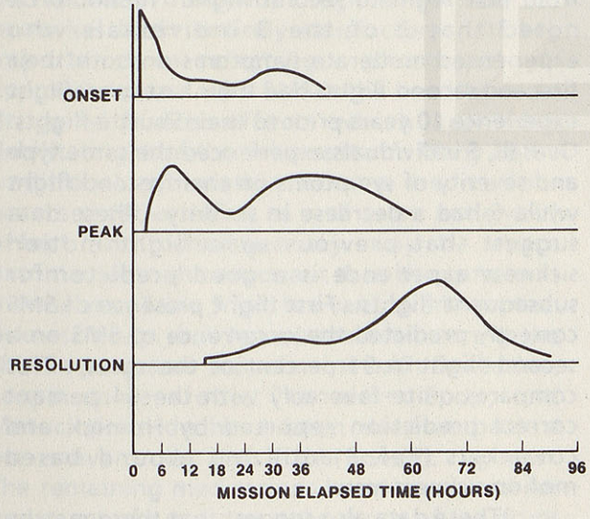

Figure 1. SMS symptom time course: all cases.

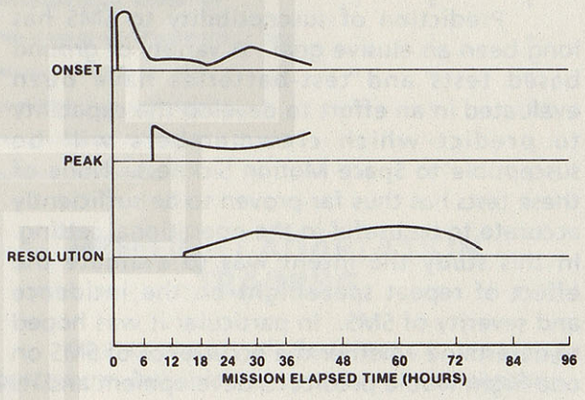

Figure 2. SMS symptom time course: mild cases.

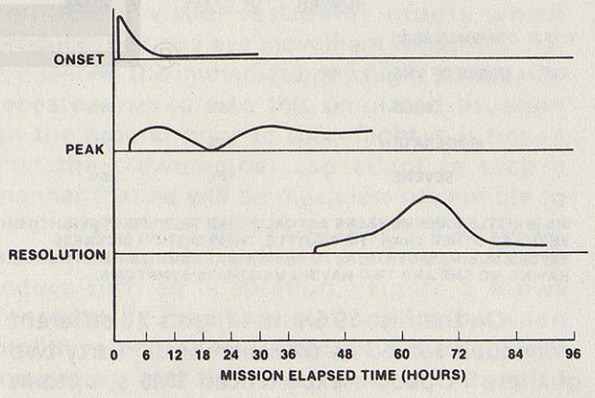

Figure 3. SMS symptom time course: moderate cases.

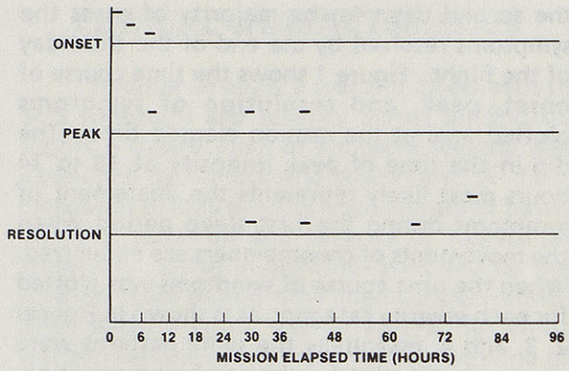

Figure 4. SMS symptom time course: severe cases.

PREDICTION

Prediction of susceptibility to SMS has long been an elusive goal. A variety of ground based tests and test-batteries have been evaluated in an effort to develop the capability to predict which crewmembers will be susceptible to Space Motion Sickness. None of these tests has thus far proven to be sufficiently accurate to be useful in the operational setting. In this study the intent was to evaluate the effect of repeat spaceflight on the incidence and severity of SMS. In particular it was hoped to determine whether the occurrence of SMS on one flight would predict its development and its severity on subsequent flights.

TABLE 6. SHUTTLE CREWMEMBERS' SMS EXPERIENCE ON FIRST FLIGHT*

	NUMBER	PERCENT OF CASES	PERCENT OF TOTAL
TOTAL CREWMEMBERS	71		
TOTAL CASES OF SMS	42		59%
MILD	18	43%	25%
MODERATE	17	40%	24%
SEVERE	7	17%	10%

*SIX SHUTTLE CREWMEMBERS ACTUALLY HAD THEIR FIRST FLIGHTS ON VEHICLES OTHER THAN THE SHUTTLE. THEIR MOTION SICKNESS EXPERIENCE WAS IDENTICAL TO THEIR FIRST SHUTTLE FLIGHT: FOUR HAVING NO SMS AND TWO HAVING MODERATE SYMPTOMS.

On the first 19 Shuttle flights 71 different individuals served as crewmembers. Forty-two of these 71 people experienced SMS symptoms on their first flight, for an incidence of 59 percent. The severity distribution of these cases is shown in Table 6.

Among the crewmembers of the first 19 Shuttle missions were 22 astronauts who flew in space more than once. Eleven of these were affected by SMS on their first flight. However, on their second flight only 9 of these 11 experienced the sickness. This represents a reduction from 50 percent to 41 percent. None of the 11 who were not sick on their first flight developed symptoms on any subsequent flight. In addition to a reduction of the total number affected by SMS on their second flights there was also a reduction in the severity of symptoms of some of those who were still sick on their second flight. These data are summarized in Table 7.

TABLE 7. SMS EXPERIENCE OF REPEAT SPACE FLIGHT

SMS INCIDENCE
FIRST FLIGHT: 11 CASES = 50%
SECOND FLIGHT: 9 CASES = 41%

PATTERN: SEVERITY	1ST FLIGHT	2ND FLIGHT
NONE	11	13
MILD	3	6
MODERATE	7	3
SEVERE	1	0

Table 8 shows the change in severity level from first flight to second flight. It should be noted that 2 of the 3 individuals who experienced moderate symptoms on both their first and second flights had their first spaceflight experience 10 years prior to their Shuttle flights. Overall, 5 individuals experienced the same type and severity of symptoms on their second flight while 6 had a decrease in severity. These data suggest that previous spaceflight motion sickness experience is a good predictor for subsequent flights. First flight presence of SMS correctly predicted the occurrence of SMS on a second flight in 91 percent of the cases. This compares quite favorably with the 64 percent correct prediction reported by Homick and coworkers (Ref. 1) utilizing ground based motion sickness tests.

These data also suggest that there may be a carryover of adaptation from one flight to the

next. Of the 9 astronauts who flew twice on the Shuttle and were sick on the first flight, 6 had a decrease in symptoms on their second flight.

TABLE 8. SMS SEVERITY CHANGE FROM FIRST TO SECOND FLIGHT

1ST FLIGHT	2ND FLIGHT	NUMBER
NONE	NONE	11
MILD	MILD	2
MODERATE	MODERATE	3
MILD	NONE	1
MODERATE	NONE	1
MODERATE	MILD	3
SEVERE	MILD	1
	TOTAL	22

COUNTERMEASURES

A search for effective and operationally useful countermeasures for Space Motion Sickness continues to be conducted by scientists both within NASA and in the academic research community. Three general areas of countermeasures--Drugs, Preflight Adaptation Training, and Autogenic Feedback Training--are under investigation at the present time.

DRUGS

Various drugs have been tried in a preventive or therapeutic regimen for SMS but none has been entirely satisfactory. Of key importance in selecting a pharmacologic approach to deal with SMS is the need to avoid drugs with side effects which are more debilitating than the sickness itself. Many of the traditional anti-motion sickness medications have a sedative effect as well as an antiemetic effect and consequently may be more detrimental to the astronaut than the symptoms themselves. Table 9 lists the various anti-motion sickness drugs that have been tried during the Shuttle program. Scopolamine with Dexedrine, Scopolamine alone, Transderm Scop, and Metoclopramide have been used in both a preventive mode and a therapeutic regimen. The remaining medications have been used for treatment of symptoms only. None of the drugs has been tested in adequately controlled studies. Consequently, conclusions about the efficacy of any of the drugs are based only on anecdotal accounts. Two lines of investigation are currently underway at the Johnson Space Center. One investigation is studying the pharmacokinetics of Scopolamine and Dexedrine inflight while the other investigation will study, in a controlled double-blind manner, the effect of Scopolamine and Dexedrine in preventing SMS.

TABLE 9. SHUTTLE CREWMEMBER ANTI-MOTION-SICKNESS DRUG USAGE SUMMARY

	NUMBER OF CREWMEMBERS		
DRUG NAME	TOTAL	WITH SMS	WITHOUT SMS
SCOPOLAMINE (.4 mg) + DEXEDRINE (5 mg) - ORAL	31	20	11
SCOPOLAMINE (.4 mg) - ORAL	1	1	0
PHENERGAN (25 mg) - SUPPOSITORY	3	3	0
PHENERGAN (25 mg) + EPHEDRINE (25 mg) - ORAL	1	1	0
METOCLOPRAMIDE (10 mg) - ORAL	22	19	3
COMPAZINE (10 mg) - SUPPOSITORY	3	3	0
TRANSDERM SCOP - CUTANEOUS	1	0	1
DIAZEPAM (5 mg) - ORAL	1	1	0

PREFLIGHT ADAPTATION TRAINING

The concept of developing training procedures by which adaptation of the sensory-motor system can be accomplished prior to spaceflight has arisen from experimental results supporting the otolith tilt-translation reinterpretation hypothesis (2 and 3). In this countermeasure concept for SMS, a training devise is used in which the subject is exposed to conflicting visual-vestibular inputs which produce the same eye movement responses that are seen in the immediate postflight period. By repeated exposure to this simulated situation on the ground prior to spaceflight it is hoped that the crewmember can adapt in such a manner that he will be much less susceptible to SMS. Preliminary studies, as reported by Parker and co-workers (3), indicate that it is possible to induce such an adaptation. Figure 5 shows conceptually how the relationships between otolith responses associated with the subject's movements and the visual scene presented to him are systematically altered. For example, in the trainer, leftward head roll results in

translation of the visual scene toward the left without rotation. It remains to be seen whether this will be an effective countermeasure for SMS.

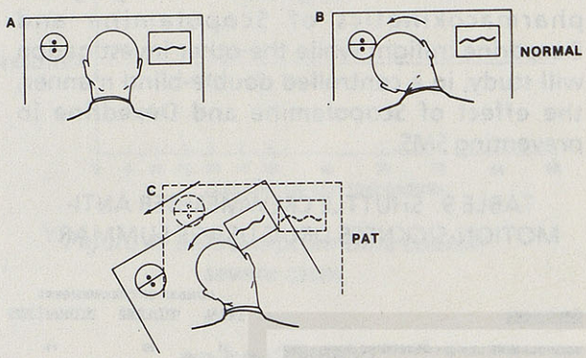

Figure 5. Concept for preflight adaptation training (PAT).

AUTOGENIC FEEDBACK TRAINING

A third area of investigation in the development of SMS countermeasures is the study of autogenic feedback training. In this technique the crewmember is taught to control certain autonomic nervous system functions, such as heart rate, skin temperature, and muscle tension, with the goal that this training will carry over into the control of motion sickness symptoms (4 and 5). This technique has been tried on two Shuttle flights under the direction of Dr. Cowings of the NASA Ames Research Center. Thus far too few subjects have been evaluated to draw a conclusion about the efficacy of this countermeasure.

SUMMARY

The incidence of space motion sickness during flights of the Space Shuttle continues to run between 50 and 60 percent. Although there has not been a serious deleterious effect on Shuttle mission objectives to date, the symptoms are unpleasant and reduce crew efficiency. The impact of SMS is potentially greater in flights which, planned or otherwise, are completed in less than four days. Approximately half of the cases of SMS are mild in nature and resolve fairly quickly. The remainder of the cases are in the moderate to severe categories and include multiple episodes of vomiting, suppression of appetite, and contribute to dehydration of the crewmembers. Most of the crewmembers who become sick do so within the first 6 hours after launch, reach the peak of their symptoms in the middle of the first or second day of flight, and feel back to normal by the end of the third day of the mission.

Previous spaceflight experience with SMS is an accurate predictor of subsequent susceptibility to the sickness. There does, however, appear to be a partial retention of adaptation from one flight to the next, particularly if the time interval between space flights is less than two years.

A search for effective and operationally useful countermeasures continues. In order for a countermeasure to be useful it not only must be effective in preventing or minimizing symptoms but must also be free of side effects which could reduce crew performance. There is active ongoing research in three general areas: anti-motion sickness drugs, preflight adaptation training, and autogenic feedback training. In all likelihood the ultimate solution to the problem will involve a combination of countermeasures tailored to each individual's specific needs.

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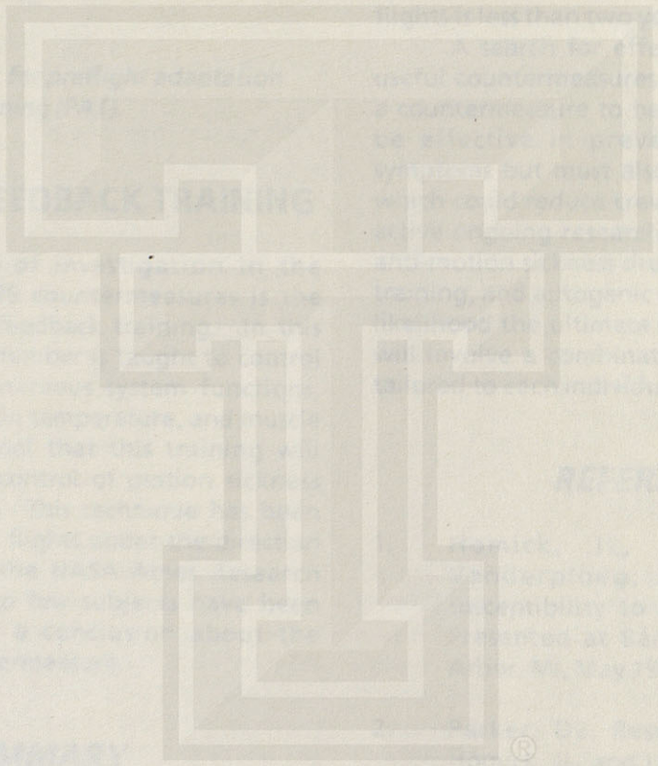

EFFECTS OF PROLONGED WEIGHTLESSNESS ON SELF-MOTION PERCEPTION AND EYE MOVEMENTS EVOKED BY ROLL AND PITCH

Investigators: M. F. Reschke, Ph.D., and D. E. Parker, Ph.D.

INTRODUCTION

Responses to three types of motion were examined before and after 5-7 days of orbital flight. Self-motion perception and eye movements were recorded during roll and pitch stimulation. Postural orientation was assessed using video tape recordings of voluntary body movements.

The research described in this paper was derived from the otolith tilt-translation reinterpretation model (1,4,5). This model suggests that on Earth the otoliths respond to both linear motion and head tilt (pitch or roll) with respect to gravity. In space, however, the otoliths no longer respond to head tilt with respect to gravity. Following adaptation to weightlessness, otolith signals apparently are interpreted by the brain as always indicating linear motion.

Three research hypotheses were examined: (i) roll or pitch stimulation would result in translational self-motion perception during reentry and immediately postflight; (ii) within the first 1-2 hr after landing, roll would elicit increased (relative to preflight) horizontal eye movements and pitch would elicit reduced vertical eye movements; (iii) overshoots in torso bending would be observed when a standing astronaut attempted to tilt (roll and pitch) 20 deg off-vertical immediately postflight.

Those parts of the first and second hypotheses concerning effects of roll were derived from data obtained from three astronauts and were reported previously (1). It was anticipated that the previous observations would be replicated.

Hypothesized response changes associated with pitch stimulation were based on the otolith reinterpretation model. If otolith signal reinterpretation persists immediately after landing, anterior-posterior displacement of the otoliths should be correlated with translation along the astronaut's X body axis and with ocular accommodation and convergence changes (but not vertical eye movements). After adaptation to weightlessness and while still on orbit, vertical eye movements during pitch head motion should be driven entirely by the semicircular canals. Immediately after landing, otolith signals associated with pitch head motion should stabilize the eye and oppose the vertical eye movement signal generated by semicircular canal stimulation; therefore, the gain of the vertical eye movement evoked by pitch should be reduced.

The third hypothesis was derived from anecdotal observations and the otolith reinterpretation model. Vestibular, proprioceptive, and visual signals normally provide feedback as a person attempts to bend from the waist to a particular tilt angle. If visual signals are eliminated and if the otolith output is not interpreted as tilt immediately postflight, the magnitude of the feedback signal during voluntary tilting should be reduced. Consequently, the astronauts should bend too far as they attempt to perform roll or pitch movements.

PROCEDURES

SUBJECTS

Eight astronauts who participated in four different shuttle missions contributed to the results reported here. Data from Astronauts 1-3 have been reported previously (1). Due to last-minute change of the landing site, postflight eye movement data from Astronauts 7 and 8 are incomplete.

APPARATUS AND PROCEDURES

The apparatus used to passively move Astronauts 1-6 during self-motion perception and eye movement recording was the Miami University Parallel Swing (1). The astronaut was restrained in the prone position with his head dorsal-flexed about 45 deg. A cloth shroud enclosed the head-end of the cylinder and eliminated motion cues from air currents and light.

For roll stimulation, the aluminum cylinder was oscillated at 0.26 Hz around the subject's Z body axis (X head axis). Roll amplitude was ±5 deg from the head-upright position for self-motion perception and ±15 deg for eye movement recording.

Preflight observations from Astronauts 7 and 8 were obtained using a newly-constructed pitch-and-roll device (PARD-Fig. 1). The astronauts were restrained by belts located at the feet, legs, hips, waist, shoulders and arms. The head was restrained by ear pads and a bite board. A light-tight shroud covered the entire body. Self-motion perception was recorded following stimulation at 0.2 Hz and ±5 deg from the head-up position. Eye movements were recorded during stimulation at 0.1, 0.2 and 0.4 Hz at ±15 deg for the higher frequencies and ±30 deg at 0.1 Hz.

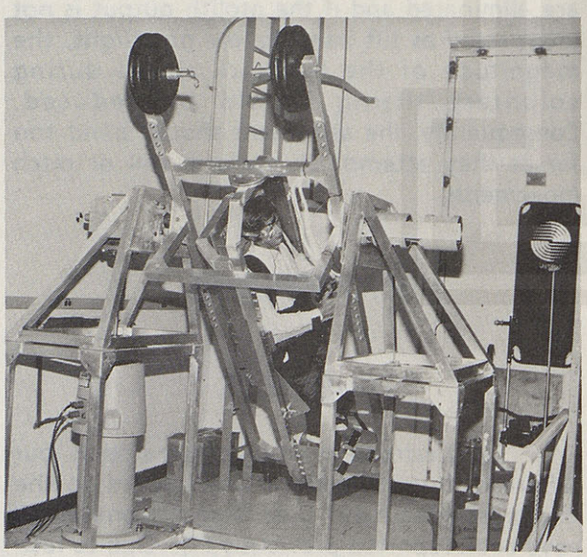

Figure 1. Pitch and roll device.

SELF-MOTION REPORTING

Responses to three motion stimuli produced by the parallel swing were obtained from Astronauts 1-6. The motions consisted of pure linear motion at 100 cm/sec/sec, pure roll at ±5 deg, and phase-locked combined roll and linear motion. Three cycles of each type of motion stimulus were presented. The data collected consisted of drawings and verbal reports (recorded on a VCR) of perceived self-motion path.

Self-motion and visual-surround-motion perception reports during pitch, roll and yaw voluntary head motion (±15 deg, 0.25 Hz) were voice recorded during reentry and while the orbiter was stationary on the runway from Astronauts 7 and 8. Less formal observations were performed by Astronauts 5 and 6. The voice tapes were reviewed with the subjects during a video-taped debriefing two days after landing.

EYE MOVEMENT RECORDING

Eye movements were recorded using an infra-red sensitive video camera and with Electrooculogram (EOG) electrodes. For the video recordings, the camera was focused on the subject's left eye with the aid of extender rings. The light source was an array of infrared-emitting diodes mounted on the camera lens. The camera output was recorded on 3/4 inch tape. For EOG recording, signals from "vertical" and "horizontal" electrode pairs were preamplified and recorded using an LSI-11/23 computer system.

VOLUNTARY TILT

The astronauts were placed adjacent to a wall on which a 20 deg off-vertical line was located. They were required to tilt from the waist until their torso was aligned with the line. Video tape records were obtained while the subjects rolled to their left or pitched forward first with their eyes open and then closed (Astronauts 4-6) or only with their eyes closed (Astronauts 7 and 8).

RESULTS

PERCEIVED SELF-MOTION

PARALLEL SWING OBSERVATIONS

Drawings indicating perceived self-motion path during roll from Astronauts 1-6 are illustrated in Fig. 2. Preflight, all reported that cylinder roll produced primarily roll self-motion perception. Immediately postflight, they reported increased horizontal displacement during the roll stimulation.

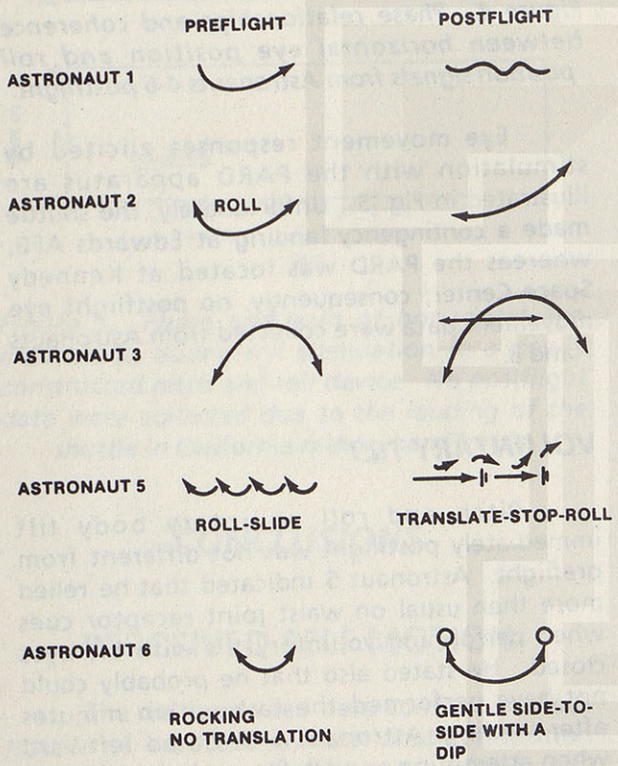

Figure 2. Drawings of self-motion perception during roll from Astronauts 1-6. The postflight reports were obtained within 2.5 hours after landing.

REENTRY OBSERVATIONS

Astronaut 6 reported self-motion perception associated with pitch, roll and yaw head motion during reentry. Forward pitch motion initially resulted in the perception of backward translation. This perception was reported as unexpected. Subsequently during reentry, pitch and roll elicited translational self-motion perception in the same direction as the head movement.

Astronaut 7 reported strong sensations of self- and surround-motion associated with pitch and yaw during reentry and after the orbiter had stopped on the runway. No unexpected sensations were associated with roll head movement. As previously reported by Astronaut 6, the translation component of the self-motion was perceived to be in the direction of the tilt. Astronaut 8 reported that head motions during reentry and subsequently on the ground made him dizzy and elicited motion sickness symptoms.

EYE MOVEMENTS

Data suitable for Fourier analysis were recorded from Astronauts 4-6 postflight and from Astronauts 7 and 8 preflight. Following digital filtering and cosine tapering, the digitized eye movement and roll stimulus records were analyzed employing Fourier transforms. Stimulus power, ocular response power, transfer function gain, phase and coherence at the stimulus frequency were determined.

Figure 3 illustrates horizontal eye movements recorded during roll stimulation from Astronaut 6 two hours (Fig. 3-A) and three days (Fig. 3-B) after landing. On the day of landing (R + 0), the horizontal eye position trace led the roll position signal by 33 deg; three days after landing (R + 3) the eye position trace led the roll signal by 165 deg.

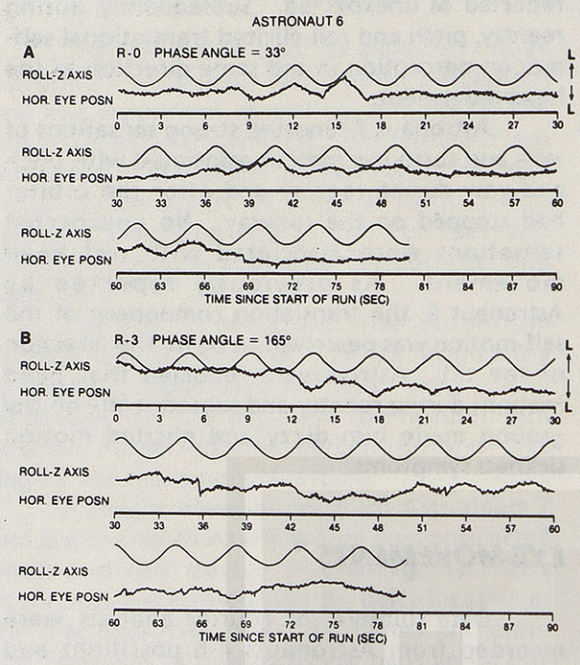

Figure 3. Eye movement records from Astronaut 6 during roll stimulation at 0.25 Hz 2 hr (R + 0) and 3 days (R + 3) after landing. Note that the phase relationship between horizontal eye movements and head roll changed.

Eye movement phase angle and coherence data from Astronauts 4-6 are plotted in Fig. 4. The EOG records from Astronaut 6 indicate a 132 deg phase shift during roll stimulation immediately postflight relative to later postflight observations. Leftward roll was associated with leftward horizontal eye movement for Astronauts 4 and 5 across all recordings and for Astronaut 6 three days after landing.

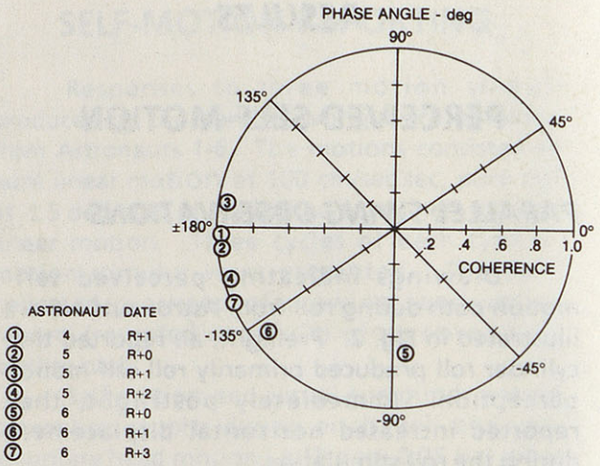

Figure 4. Phase relationships and coherence between horizontal eye position and roll position signals from Astronauts 4-6 postflight.

Eye movement responses elicited by stimulation with the PARD apparatus are illustrated in Fig. 5. Unfortunately, the shuttle made a contingency landing at Edwards AFB, whereas the PARD was located at Kennedy Space Center; consequently, no postflight eye movement data were collected from Astronauts 7 and 8.

VOLUNTARY TILT

Pitch and roll voluntary body tilt immediately postflight was not different from preflight. Astronaut 5 indicated that he relied more than usual on waist joint receptor cues when performing voluntary tilt with his eyes closed. He stated also that he probably could not have performed the task within minutes after landing. Astronaut 6 deviated leftward when attempting to pitch forward and reported "digging in" his toes.

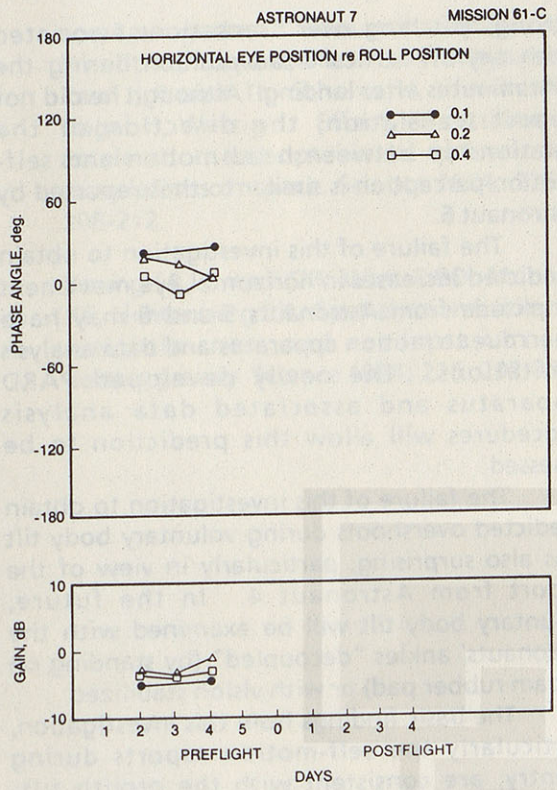

Figure 5. Phase and gain of horizontal eye movements during roll stimulation in a newly constructed pitch and roll device. No postflight data were collected due to the landing of the shuttle in California rather than Florida.

CONCLUSIONS

PERCEIVED SELF MOTION

The data reported here confirm previous reports of increased translational self-motion perception during roll stimulation immediately after extended orbital flight. The reports from Astronaut 6 and 8 regarding perception during reentry strongly confirm the basic observations.

Three astronauts performed slow pitch and roll head motions during reentry or while stationary on the runway immediately after a mission. All three reported unusual self- or surround-motion perception while performing the head movements. Astronaut 6 reported self-motion initally in the direction opposite to the head tilt and subsequently in the same direction as the tilt. Astronaut 8 reported that his perception of translational self-motion was always in the direction of the head tilt.

Following the otolith tilt-translation reinterpretation model, we hypothesized that weightlessness-adapted astronauts would report translational self motion in the direction opposite to head pitch or roll immediately postflight. Figure 6 summarizes a possible resolution of the discrepancy between this prediction and the astronauts' reports.

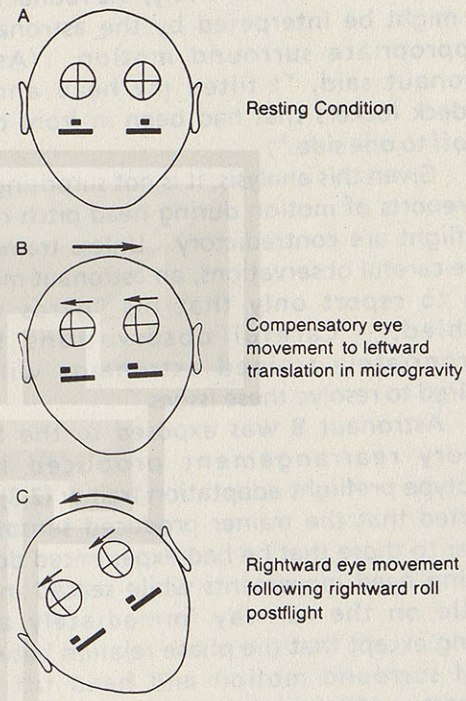

Figure 6. Otoconia displacement and associated compensatory horizontal eye movements developed during adaptation to microgravity.

An astronaut's eyes and the otoconia located above the utricular maculae are illustrated in Fig. 6-A. In microgravity, leftward translation would be associated with rightward displacement of the otoconia and a rightward compensatory horizontal eye movement, as illustrated in Fig. 6-B. When the astronaut returns to a gravity environment, rightward head roll would produce rightward displacement of the otoconia. If he relies only on the signals from the otolith organs, the astronaut should perceive leftward translational self motion because rightward otoconia displacement has been associated with leftward translation during adaptation to microgravity. Alternatively, suppose the astronaut's eyes are

open while he rolls his head. The rightward compensatory horizontal eye movement developed during adaptation to weightlessness should persist (Fig. 6-C). This compensatory eye movement would cause the image of the stationary visual surround to slip across the retina in a leftward direction. This leftward retinal slip could be interpreted by the astronaut as rightward self motion in the same manner as the well-known linear and circular vection reactions. Conversely, the retinal image slip might be interpeted by the astronaut as inappropriate surround motion. (As one astronaut said, "I tilted my head and the middeck lockers that had been in front of me slid off to one side.")

Given this analysis, it is not surprising that the reports of motion during head pitch or roll postflight are contradictory. Unless trained to make careful observations, an astronaut may be able to report only that his "gyros were tumbled." Careful observations from appropriately trained astronauts will be required to resolve these issues.

Astronaut 8 was exposed to the basic sensory rearrangement produced by a prototype preflight adaptation trainer (2,3). He reported that the trainer produced sensations similar to those that he had experienced during pitching head movements while seated in the shuttle on the runway immediately after landing except that the phase relation between visual surround motion and head tilt was incorrect by 180 deg.

EYE MOVEMENTS

The altered head movement/eye movement phase relationship recorded from Astronaut 6 was not found for Astronaut 5. This may be due to the fact that the observations were performed with Astronaut 5 about 45 minutes after those with Astronaut 6. Consequently, he may have been more completely readapted to the normal-gravity environment. Alternatively, this may reflect individual differences in adaptation or readaptation processes.

Astronaut 5 reported erratic self motion/head motion relationships during reentry and that locomotion during this period was guided solely by visual cues. He reported strong "pitching over" sensations associated with any off-vertical head position during the first minutes after landing. Although he did not report translation, the direction of the relationship between head motion and self-motion perception is similar to that reported by Astronaut 6.

The failure of this investigation to obtain predicted increases in horizontal eye movement amplitude from Astronauts 5 and 6 may have been due to motion apparatus and data analysis limitations. The newly developed PARD apparatus and associated data analysis procedures will allow this prediction to be assessed.

The failure of this investigation to obtain predicted overshoots during voluntary body tilt was also surprising, particularly in view of the report from Astronaut 4. In the future, voluntary body tilt will be examined with the astronauts' ankles "decoupled" (by standing on a foam rubber pad) or with vision stabilized.

The basic findings from this investigation, particularly the self-motion reports during reentry, are consistent with the otolith tilt-translation reinterpretation model and the concept for preflight prophylactic adaptation training (1).

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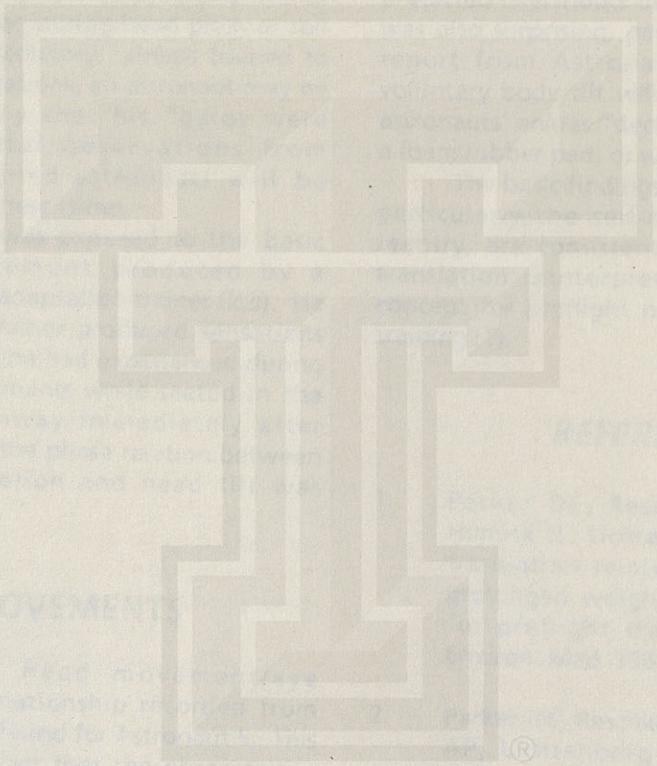

GASTRO-INTESTINAL MOTILITY IN SPACE MOTION SICKNESS

Investigators: William E. Thornton, M.D., Tom Moore, M.D., and Sam Pool, M.D.

INTRODUCTION

Motion sickness (MS) signs and symptoms have traditionally been divided into those of 'head' and 'stomach', with nausea and vomiting being cardinal signs. With adequate stimulus, vomiting is the final stage of motion sickness (14). With continued stimulus repeated vomiting may occur, to the point of prostration in some cases (15).

The neurological control mechanism for emesis has been studied and discussed in detail (2,4,19) and a simplified rendition of the currently accepted scheme of this mechanism is shown in Figure 1. There are connections from the vestibular system to the vestibular nuclei and from the nuclei to the emesis center, which produces vomiting by way of the respiratory and abdominal musculature plus some gastroduodenal activity.

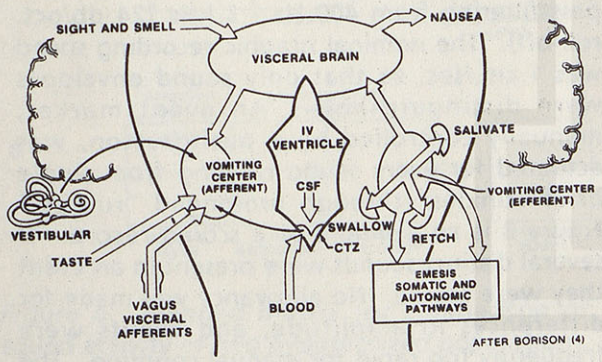

Figure 1. Currently accepted schema of emesis center and its major inputs. The center itself coordinates and directs the action of vomiting by stimulation of the respiratory and somatic abdominal musculature with some G.I. activity. After Borison.

Many investigators report the nausea of motion sickness to be accompanied by a reduction of gastrointestinal activity (16). Others have found that vestibular and other stimulation produces strong duodenal antiperistalsis (1,10). Crampton reported that vomiting in MS-susceptible cats can be prevented by plugging the aqueduct between the third and fourth ventricles, implying a possible cerebral spinal fluid (CSF) carrier role with a humoral pathway (6). Several investigators have shown decreased GI motility accompanied by increased endorphin levels with caloric stimulation (17,18). Borison found that the Chemoreceptor Trigger Zone (CTZ, area postrema) is not necessary for vomiting from motion sickness in cats (3).

The current theory is that as stimulus duration/intensity increases, hypersalivation, swallowing, nausea, and finally retching/vomiting will occur. If the stimulus level is maintained vomiting will be repeated. At lower stimulus levels only salivation or nausea may be sustained. Less frequently, nausea and vomiting may occur suddenly with or without any or all of the prodromal symptoms.

Early in the Shuttle program there were reports of sudden, brief bouts of vomiting without prodrome (including nausea). Considerable periods of time, usually hours, could elapse before the event was repeated unless food or water was ingested, in which case vomiting typically followed in less than an hour. Vomitus was usually clear, but occasionally bile stained. Any food present was undigested. There were one or two reports of vomiting coincident with seeing the Earth "inverted" but such cases were a small minority; it usually occurred in ordinary circumstance and often with lights out. Nausea was sometimes present, but was more often absent.

Vomiting of this nature was so different from that of ordinary motion sickness that a crewman who had experienced both summed up his opinion by stating, "I don't know what it is but it isn't sea sickness!" This difference was one of the major reasons for an inflight investigation begun by the Astronaut Office and Flight Medicine. As part of this

investigation, an on-board physician noted that bowel sounds were absent in those with Space Motion Sickness (SMS) for the duration of the syndrome but present after recovery and in those unaffected. It was concluded that the GI problem was a temporary ileus. Electronic recording of bowel sounds and direct and electronic ascultation performed on one flight confirmed the earlier findings. Metoclopramide (MCP) was taken in an attempt to reestablish bowel activity and seemed to be effective in two subjects.

An improved sound recording system was devised and 18 inflight records of sounds have been made, including 6 during SMS and 3 while taking MCP. An electro-gastro-graphic study was done on 1 subject, a single trial of intravenous MCP and Naloxone was done, and frozen plasma from 2 subjects with SMS was obtained for analysis of possible transmitter substances. The following results are from an ongoing study.

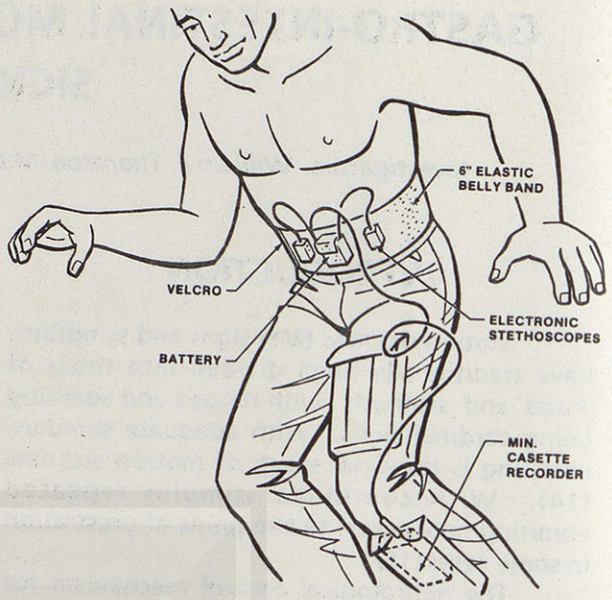

Figure 2. Inflight recording of bowel sounds. The recorder is small enough to be carried in a pocket.

PROCEDURES

Electronic stethoscopes (with a battery life of 14 days) were incorporated into an elastic, velcro-secured belt (Figure 2). They were located over the right and left upper quadrants of the abdomen. Output was recorded by a professional quality, miniature dual channel tape recorder typically carried in a flight suit pocket. Frequency response of the microphones was 30 to 500 Hz (3 db. points) in contact with skin. They were embedded in foam to improve the sealing of the microphone cavity to the body. Validated frequency response of the recorder was 40 to 15,000 Hz (3db), with 1 percent distortion and wow and flutter of less than 0.14 percent with a speed accuracy of 0.3 percent. Cassette tapes with 45 minutes recording time per side were used. No attempts were made to control conditions or activities during the recording period, including ingestion of food, since this would have inevitably conflicted with inflight operations and would have further reduced recording opportunities. Where possible, the conditions were documented.

Data were reduced by the investigator by monitoring both channels of the recorded sounds with wide response earphones. Sounds were graphically recorded by a high-frequency (DC-15 kHz) electrostatic recorder after band pass filtering from 400 Hz - 3 kHz (24 db/oct. roll-off). The nominal graphic recording speed was 1 cm./sec. so that only sound envelopes were distinguishable. An event marker, manually controlled by a push button, was actuated for every sound ranging from single brief "tinkles" through prolonged "rushes." Figure 3 is an example of a scored record. If several distinct sounds were present in an event they were scored. No allowance was made for differences in amplitude, and events were frequently too rapid for manual counting. The result was that a quiet bowel was overscored and an active one underscored. Obviously, this was semiquantitative at best. The events were counted for each one minute epoch, summed, and plotted for 5 minute epochs.

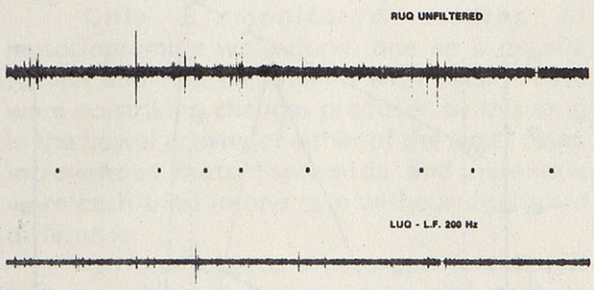

Figure 3. Section of a scored bowel sound recording made inflight on one mission. Identified sounds are indicated by the marker signals between channels.

The planning matrix in Figure 4 was done to allow the comparisons shown. Twenty recordings were also made before, during, and after acutely induced MS on the rotating chair using this system on ordinary subjects. A series of recordings over extended periods during normal activities was also made.

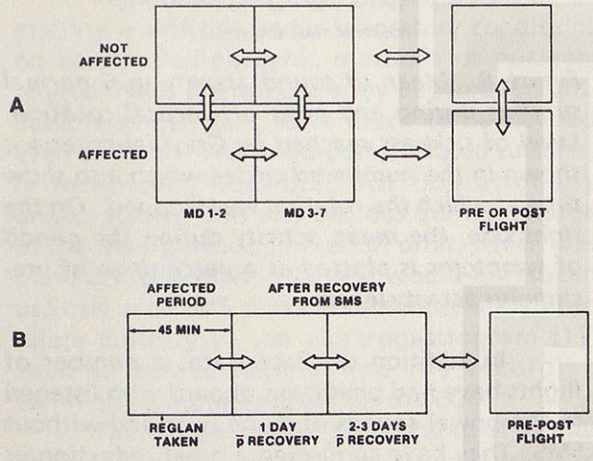

Figure 4. Planned matrix for comparison of sound activity of two hypothesized populations, affected versus unaffected, plus another with medication, in 3 possible circumstances. 'A' allows comparison of affected versus unaffected under various conditions while 'B' examines the effect of MCP on individuals affected.

RESULTS

Nineteen individuals have made at least 1 recording inflight. Of these, 6 affected subjects, one of whom flew 3 times, have made recordings that met the horizontal or temporal requirements of the study; i.e., 1g baseline and recording during and after SMS. None of these had simultaneous inflight controls. One subject, unaffected by SMS, made an adequate total number of recordings. Two of the recordings included the use of MCP. Other recordings were randomly scattered in time.

The collected data does not allow for significant comparisons as planned (Figure 4) other than between the level of activity preflight and inflight during SMS in those affected, and between those affected and unaffected during the same periods.

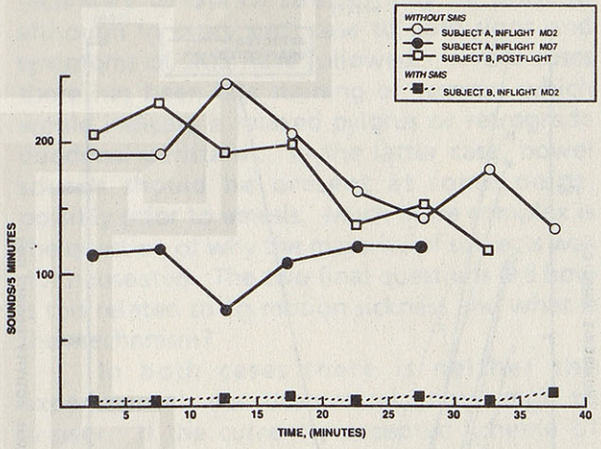

Figure 5. Plot of means of sounds counted per five minutes versus time during the period of SMS inflight and after recovery. Subject A was unaffected while B had a typical course of SMS. Inflight MD2 on subject A was made during the susceptible period while inflight MD7 was made after this period.

Typical plots of sound activity versus time for individuals with and without SMS are shown in Figure 5. Of particular interest was one recording made over the period of recovery. In Figure 6, the 5-minute means of counts are shown over this period. The means of such activity for all subjects versus the period in which they were gathered are plotted in Figure 7. Normalized activity, i.e., counts during the period of SMS divided by 1g baseline counts, are also plotted here.

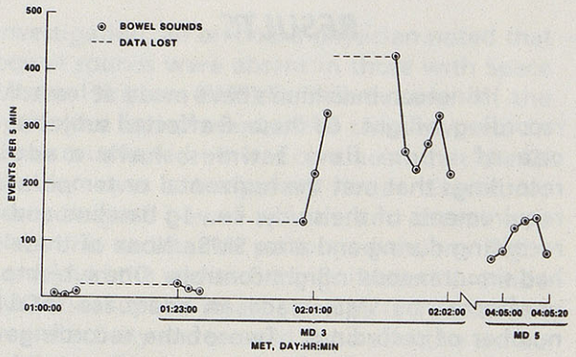

Figure 6. Record of sound activity from a subject during recovery from SMS. The rapid resolution and period of hyperactivity is consistent with indirect observations of this process. MET is mission elapsed time and MD is mission day; i.e., recordings on MD3 were made on the morning of the third day.

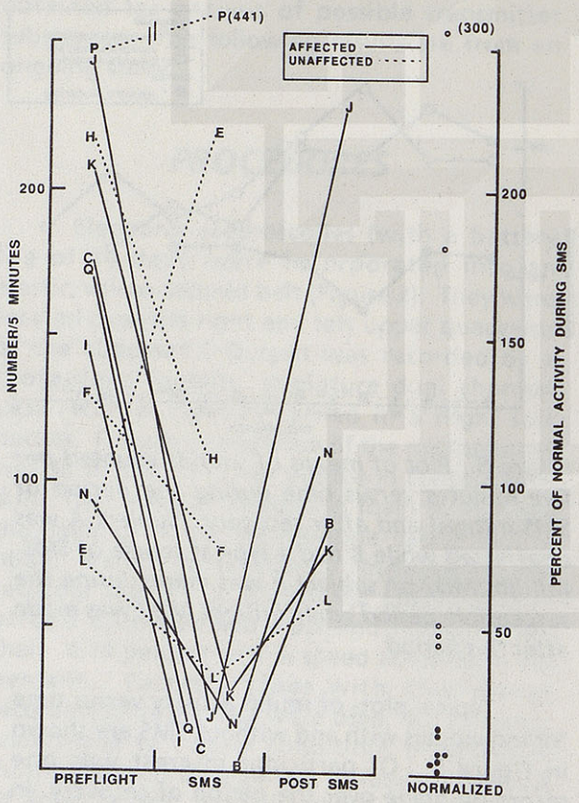

Figure 7. Means of counts from recordings made of all subjects, preflight and during periods of SMS and recovery. Affected individuals have solid lines, while those unaffected are dotted. Percentage of activity during SMS versus preflight are plotted on the right side with those affected in solid circles and those unaffected in open circles.

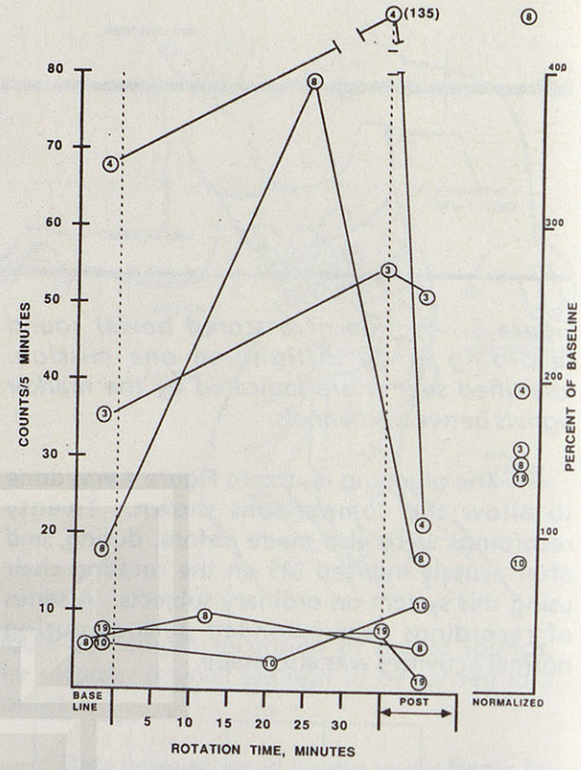

Figure 8. Mean of sound activity in 6 normal subjects during and after off-vertical rotation. Level of sickness reached by Graybiel criteria is shown in the numbered circles which also show time at which the rotation was stopped. On the right side, the mean activity during the period of symptoms is plotted as a percentage of pre-stimulus activity levels.

In addition to these data, a number of flights have had physicians aboard who listened to the bowel sounds of those with and without SMS. They have confirmed a great reduction or virtual absence of sounds in those with SMS as compared to activity after recovery or in those without SMS. Such reductions have been observed in all but one case of recorded or observed subjects to date. One subject appeared to develop marked hyperactivity during SMS, but medication was present. In contrast, most who were unaffected have had normal or hyperactivity during this period. The change was so striking that a number of nonmedical astronauts have monitored their gut activity with stethoscopes. The sound activity of normal subjects with acutely induced MS is shown in Figure 8. In every case monitored during off-vertical rotation, the activity was increased or unchanged.

Only 3 monitored studies of metoclopramide were done; one on a normal subject and two on subjects with SMS. There were no striking changes produced by this drug in the bowel activity of either of the latter cases. Intravenous metoclopramide and naloxone were each tried in one case without significant difference.

On one subject, a naso-gastric catheter with transducer was passed from oral cavity to duodenum, and pressure recordings were obtained, but this was after recovery from SMS. It probably would not have been possible during SMS.

There have been numerous ground-based electrogastrogram (EGG) studies, but only one flight study has been performed, and that was after SMS had resolved.

CONCLUSIONS

Reasonably accurate measurement of GI motility is difficult under laboratory conditions on Earth. Radiographic methods or nuclear-tagged meals are not currently possible inflight. Radiotelemetry pills leave much to be desired even on Earth. The multi-port perfused catheter is technically feasible, but operationally unacceptable. This was obvious during passage of the naso-gastric catheter on orbit, which was more difficult than in 1g and would have been unlikely with SMS present. It is more difficult to relate motility to the electrogastrogram (11) than to bowel sounds, and the recording technique is more complex for the EGG.

There is an indirect relationship of sounds to mechanical activity and especially to coordinated activity (5,7,8,9,12,13,20). Conversely, life and death decisions are still routinely based on this technique. In short, it was the best that could be done under the circumstances. The methodology is robust and reliable albeit inefficient and time-consuming, requiring approximately two times the actual recording time for assessment.

In addition to the limitations inherent in estimation of motility by auscultation there is also the wide variation that may occur with uncontrolled sampling; for example, the large changes in normal activity level from mealtime to mealtime, and under other conditions.

In spite of this and with the limited results, it seems safe to say that a significant ileus is present in the majority of subjects during SMS, and appears to last for the duration of symptoms. Such a state of the bowel is also consistent with other signs such as the vomiting of virtually all ingested food and in most cases any significant amounts of water. The vomiting of true SMS is therefore probably secondary to distension of the stomach which then stimulates the emesis center by vagal afferents. There are many and varied ramifications and possible complications of this simple scheme, both in practice and theory.

Some of the facts that must be accounted for include: vomiting may occur within minutes of orbital insertion, long before significant accumulation of liquids could occur. It seems likely, in this case, that simple motion sickness secondary to launch stresses may be present, although in every such case to date signs and symptoms of SMS have followed. In rare cases there has been bile staining of vomitus which would indicate a relaxed pylorus or retrograde duodenal peristalsis. In the latter case, bowel sounds should be present at some point, possibly prior to emesis. Much more complex is the question of why the majority of subjects was not nauseated. The two final questions are how is this related to 1g motion sickness and what is the mechanism?

In both cases there is neither the experimental, nor theoretical knowledge to answer. If the currently accepted scheme of vestibular (system) conflict → emesis center → nausea/vomiting is correct, then it seems at odds with the findings here. The question of GI activity during 1g motion sickness has not been satisfactorily answered, for while some investigators find reduced or absent activity, others have reported increased sounds and duodenal anti-peristalsis with caloric stimulation. This limited study of sounds in acutely induced motion sickness supports increased gut activity which may well be retrograde.

As to the mechanisms of this ileus, there is no certainty. At first glance it would seem to be simple vagal inhibition; but in view of animal and human studies which show large changes in endorphin levels and upper GI motility with caloric stimulation, and the blocking of effects of endorphins on motility in animals, it may not be this simple. A further note of caution may

have been raised by recent studies of Koch and Stern (personal communication) in which vagotomized patients had gastric responses to motion sickness stimulation by circumvection.

The failure of MCP and Naloxone[a] was disappointing, for if some agent could be found to restore motility a major portion of the SMS problem might be resolved. It appears that we may have to await more knowledge of the GI system itself, as well as a better understanding of brain-gut pathways to attack the ileus logically.

A better means of motility measurement is needed, and while the bowel sound methodology could obviously be improved, there is little else of promise at this time.

Conversely, the absence or reduction in bowel sounds is the first consistent sign, the first reliable marker, of SMS. It promises to be an objective means of detecting and following SMS and also offers a research path to increased knowledge of SMS, possibly back to its origin.

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(a) An n of 1 cannot be unequivocably called a failure, but it produced absolutely no effects in a good trial case.

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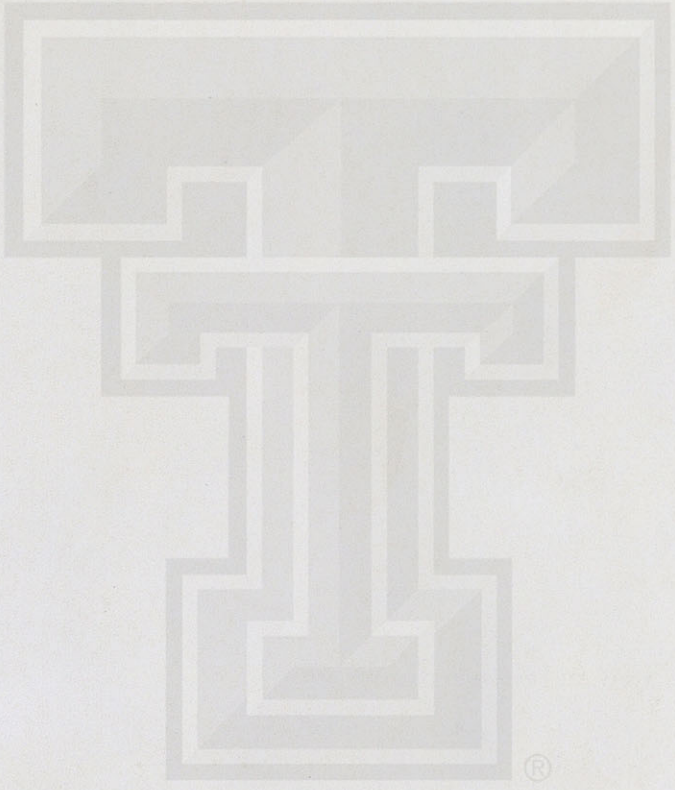

OCULAR COUNTERROLLING

Investigators: M. E. Reschke, Ph.D., D. E. Parker, Ph.D., and N. Skinner

The Otolith Tilt-Translation Reinterpretation (OTTR) hypothesis says in part that adaptation to space flight is a function of sensory rearrangement and that signals from the otolith organs during orbital flight are reinterpreted as linear displacements.

An important question relating to this concept concerns the maintenance or substitution by other sensory systems of information to the central nervous system which will replace missing or altered vestibular inputs. Specifically, this study asks the question: "Can neck receptors substitute for otolith receptor input to maintain ocular torsion during space flight?"

The measurement of ocular torsion is difficult under the best of circumstances. When coupled with the additional constraints imposed by orbital flight, very careful consideration had to be given to the mechanism and procedures that were to be used. The device and procedures had to be simple enough that the experiment could be performed by one crewperson at a time, while meeting size, weight, and safety requirements.

To meet these criteria a method of measuring ocular torsion first used about 140 years ago was selected. In this method an after-image of a target is formed on the retina. Any eye torsion occurring while the after-image is visible produces a tilting of the after-image relative to an objective reference target.

Figure 1 shows the apparatus developed to obtain ocular torsion with the after-image method. This device is a goggle arrangement housing an electronic flash to place the after-image on the retina, and a digital read out to indicate angular position of the target. A small voice-activated tape recorder was attached to the goggle so that the subjects could verbally report the position of the target as well as their head position. A neck brace was used to eliminate proprioceptive cues from the neck as a control measurement during the flight.

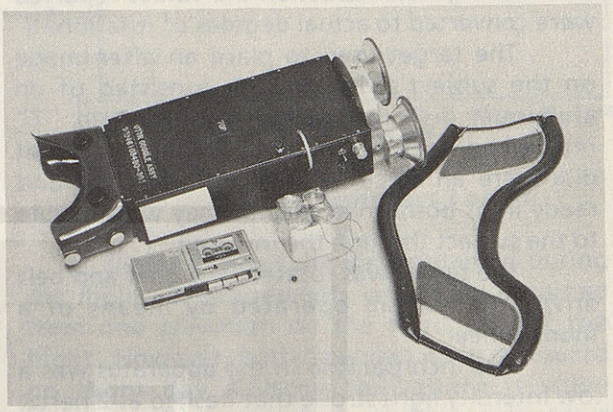

Figure 1. Ocular counterrolling measurement goggles, voice recorder, neck brace, and battery pack.

During use, the head was held in place with a set of flexible rubber eye goggles that were fixed to the main body of the device. A wide velcro strap was used to secure the head to the goggles. The device was fixed to a smooth wall for ground-based testing or to the forward bulkhead lockers during flight with a set of large suction cups. The interface between the main body of the goggle assembly and the suction cups was fitted with a tilt mechanism. This allowed the goggles to be tilted in 15 degree increments from the horizontal position up to plus or minus 60 degrees. Each position had a positive engagement detent to hold the goggles at the desired angle. Each of the nine possible tilt positions was marked with a letter rather than the actual degree of rotation to limit knowledge of head position. During ground baseline testing a level was used to insure that the goggles in the zero tilt position were perpendicular to the gravity vector.

Upon looking into the goggles, the subject saw a digital display indicating the amount of target rotation. The digital display provided a 2000 count output for displacements between plus and minus 20 degrees. This allowed a resolution of 1.2 minutes of rotation

per count. There was a small amount of hysteresis in the controls used to move the reference target and in the potentiometer used for measurement of the angular torsion. This resulted in an absolute accuracy of 10 minutes of rotation.

During the execution of this experiment the subject verbally reported the digital read out. During data reduction the values reported were converted to actual degrees of rotation.

The target used to place an after-image on the subject's right retina consisted of an aluminum disk into which an inverted "T" reticle had been machined. Behind the target disk were an electronic photo flash tube and ready light positioned so that they were visible to the subject through the inverted "T."

The target was rotated by a gear and belt driven mechanism operated by means of a thumbwheel.

Also incorporated in the apparatus was a low intensity light strobe that flashed at 2 hertz. This stroboscopic illumination refreshed the retinal after-image.

During pre- and postflight data collection, the subject set the target to the gravitational vertical with the thumbwheel. The vertical position corresponded to a value of 1000 on the digital display. Then, while following a checklist, the subject tilted his head and the goggles to a predetermined and randomized angle. Once the subject achieved the tilt angle, that position was maintained for approximately 30 seconds. Following the 30 second period the electronic flash was enabled and triggered to place an after-image on the retina.

With the after-image in place, the subject returned the goggles to the upright position. The subject shut his eyes and displaced the target slightly with a thumbwheel in either the clock wise or counterclockwise direction. Once the target was displaced from the vertical, the subject opened his eyes, set the target reticle with the thumbwheel so that it matched the angular position of the after-image, and read a displacement value from the LED's. The subject repeated this procedure in the upright position twice more for that angle, always displacing the target in the opposite direction between each measurement. This entire procedure was then repeated for each of the remaining 8 angles of head tilt.

The inflight procedures differed only slightly from those used on the ground. In one condition the subject's feet were restrained in foot restraints. This condition required the subject to flex his neck to obtain the tilt angles just as he did on the ground. The control condition required the subject to wear a neck brace and to float freely such that his whole body was tilted to match the angle of the goggle tilt.

Measurements were obtained during one Shuttle flight. It was hoped to have measurements made as early inflight as two or three hours. Unfortunately, the goggle unit failed during its early use. However, the crew was able to repair it and obtain data beginning on the third day of the flight.

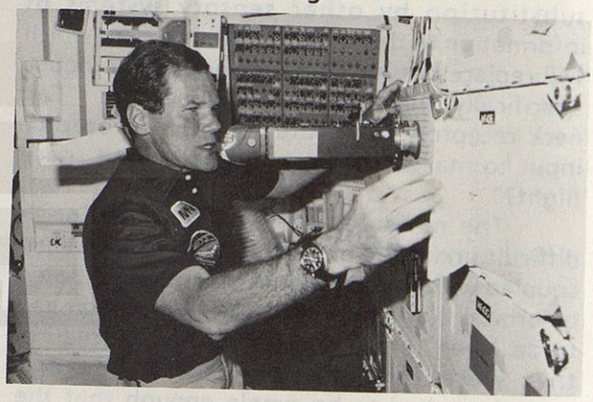

Figure 2. The ocular counterrolling measurement goggles in use during flight.

Figure 3 shows the preflight average response obtained from the two crewmen that were tested. The amount of eye torsion is indicated on the y-axis, and the head tilt position is located on the x-axis.

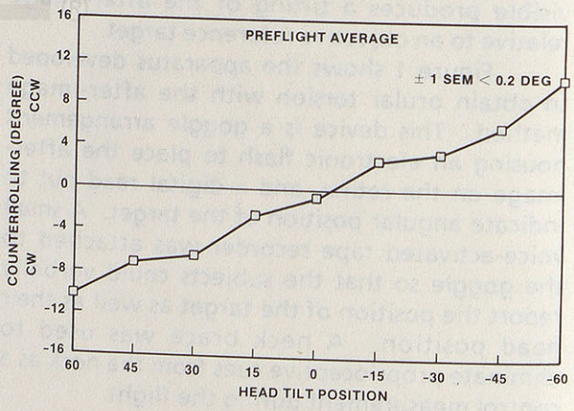

Figure 3. Preflight average data.

Four preflight measurements were obtained from one crewman and 6 from the second crewman. Each point on the plot represents 30 trials at that angle of head tilt. The variance for each data point, expressed as plus or minus one standard error of the mean, was less than 0.2 degrees.

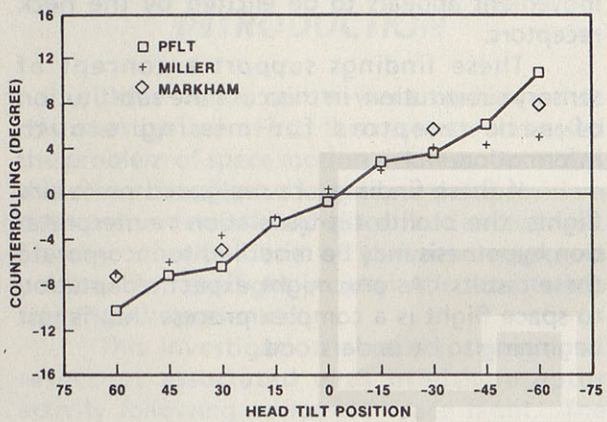

Figure 4. Preflight average vs. published data.

Because the method of measuring ocular counterrolling that was chosen is subjective in nature, it was interesting to compare these data with those from others who had used a more objective approach.

Figure 4 illustrates the preflight average data compared with data that have been published both by Miller (1) during his time at Pensacola and by Dr. Charles Markham (2). Note that for the range between plus or minus 15 degrees the data are comparable. It is at the extremes that this study shows a greater degree of eye torsion than the more objective camera data. However, the lack of correspondence between these data and those of others has no impact on the primary objective of this experiment.

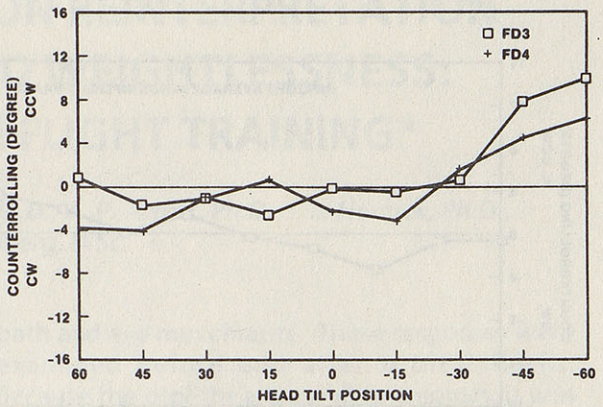

Figure 5. Data for flight days 3 and 4.

Figure 5 shows the data obtained during the flight. Measurements were only obtained from one crewman on the third day of the flight. However, both crewmen were measured on flight day 4. Note that there is some counterrolling present particularly to a rightward head tilt and that there appears to be more torsional eye movement to a head tilt early in the flight.

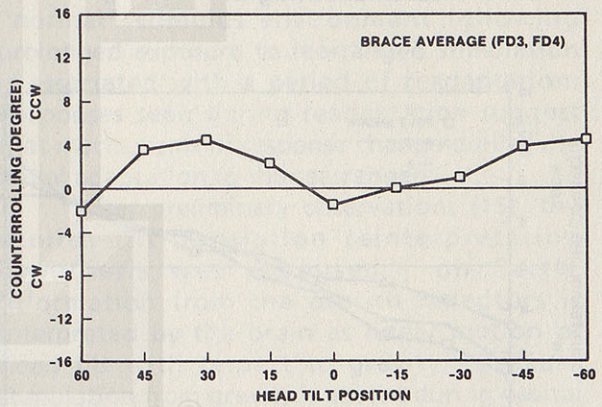

Figure 6. Neck brace average data.

Figure 6 shows the data obtained when the neck brace was worn. Note that the data appear random and do not exhibit a particular trend.

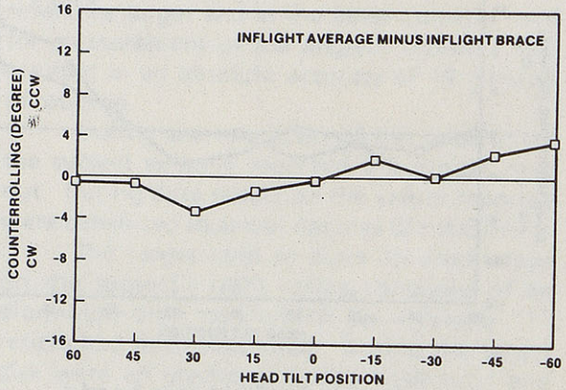

Figure 7. Inflight average minus inflight brace data.

Because of the variability of the data obtained with the neck brace, the absolute difference between the inflight experimental trials and the inflight control data was taken. That difference is depicted in Figure 7. Note that very little eye torsion is evident. The amount that is present represents the variability of this measurement inflight.

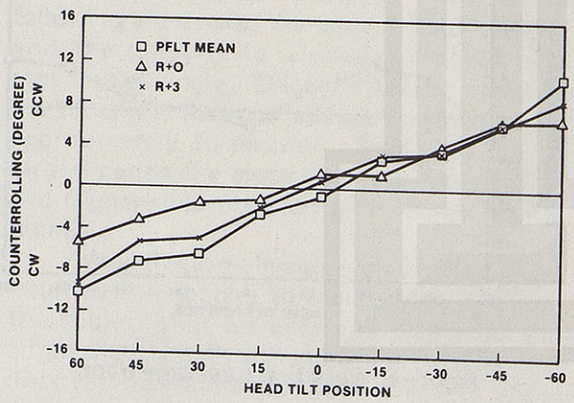

Figure 8. Postflight data.

Figure 8 shows the torsional eye data obtained after the flight. The eye movements measured immediately after the flight show some slight reduction from those obtained preflight. By the third day postflight the amount of counterrolling was essentially equivalent to that seen prior to the flight. This trend was particularly noticeable to a leftward head tilt. It is interesting to note that the compensatory eye movements to a left-ward tilt inflight showed the greatest reduction.

CONCLUSIONS

Based on the data obtained from a single flight with only two subjects it appears that the eyes show a compensatory torsional movement to head tilt. This compensatory torsional eye movement appears to be elicited by the neck receptors.

These findings support a concept of sensory substitution, in this case the substitution of neck receptors for missing otolith information.

If these findings are replicated on future flights, the otolith tilt-translation reinterpretation hypothesis may be modified to incorporate these results. As one might expect, adaptation to space flight is a complex process that is just beginning to be understood.

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OTOLITH TILT-TRANSLATION REINTERPRETATION FOLLOWING PROLONGED WEIGHTLESSNESS: IMPLICATIONS FOR PREFLIGHT TRAINING*

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INTRODUCTION

Three major points were considered in this investigation. First, this research addressed the problem of space motion sickness. Secondly, this research suggested concepts that provide a basis for understanding space motion sickness. Thirdly, on the basis of these concepts, a proposal for preflight prophylactic adaptation training was presented.

This investigation assessed changes in responses associated with otolith receptor activity following prolonged space flight. The results led to the development of an otolith tilt-translation reinterpretation hypothesis which, in conjunction with the sensory conflict hypothesis, provides a conceptual framework for comprehending space motion sickness.

Possible effects of weightlessness on spatial orientation system (13) responses have been considered by several investigators during the past two decades (10). Some have focused on the consequences of altered stimulation of the otolith receptors while others have suggested changes in the "gains" assigned by the brain to orientation information from visual, vestibular, and somatic receptors (9, 10, 13).

The vestibular otolith receptors respond to linear motion and gravity. If motion cues from visual and skin receptors were reduced or eliminated, responses to roll and linear translation attributable primarily to the otolith receptors could be examined. The Miami University parallel swing and its associated restraint system allowed this.

This investigation examined two types of responses associated with roll and linear translation stimulation: perceived self-motion path and eye movements. These responses were examined before and after orbital flight. Because the otoliths are gravity receptors, it was hypothesized that adaptation to the loss of stimulation due to gravity during flight would alter responses to which the otoliths contribute.

Both perceptual and motor responses associated with the vestibular receptors adapt to rearrangements of either vestibular or visual stimulation. This adaptation phenomenon accounts for the observation that motion sickness symptoms resolve during the initial 48-72 h of orbital flight. Rearrangements that have been investigated previously include ocean travel, slow rotation, image reversing glasses and weightlessness (3,7,17,23). Return to a "normal" stimulus environment following prolonged exposure to rearranged stimulation is associated with a period of readaptation. Responses seen during readaptation suggest that mechanisms of response change during the initial adaptation to the rearrangement.

After preliminary observations (15), the otolith tilt-translation reinterpretation hypothesis was proposed: on Earth, information from the otolith receptors is interpreted by the brain as linear motion or head tilt with respect to gravity. Because stimulation from gravity is absent during orbital flight, interpretation of otolith responses as tilt is meaningless. Therefore, the brain adapts to weightlessness by reinterpreting all otolith receptor output as linear motion (Fig. 1). Immediately following return to earth and before the brain readapts to the normal gravity environment, this reinterpretation of otolith responses persists.

Following the otolith tilt-translation reinterpretation hypothesis, it was predicted that roll stimulation would elicit roll self-motion perception preflight but that this stimulation would be associated primarily with linear

*Originally printed in Aviation, Space, and Environmental Medicine, June 1985.

translation self-motion perception immediately postflight.

It was also predicted that roll stimulation would elicit increased horizontal eye movements and decreased ocular counterrolling immediately postflight relative to preflight and later postflight observations. Vestibular-ocular reflexes serve to stabilize the direction of gaze during head motion. If the weightlessness-adapted brain interprets otolith signals as indicating translation, the appropriate compensatory eye movement during head roll would be horizontal eye deviation.

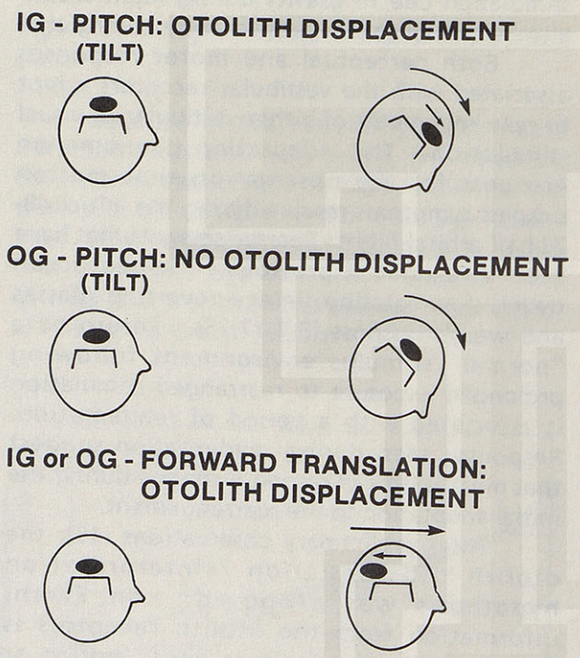

Figure 1. Diagram of vestibular otolith displacement.

PROCEDURES

PERCEIVED SELF-MOTION PATH

SUBJECTS

Three astronauts from two missions served as the subjects in this experiment.

APPARATUS

The motion apparatus employed was the Miami University Parallel swing (Fig. 2). The swing was a four-pole pendulum that produced "linear" (translation) oscillation at 0.26 Hz. For translation, the swing was moved manually by the experimenter. The swing restraint system included an aluminum cylinder which was connected to a motor drive and could be rolled at amplitudes up to ±20° and frequencies between 0.1 and 0.5 Hz. Objective measures of translation and roll motion were provided by appropriate transducers.

The subject was encased in a styrofoam body mold inside of the aluminum cylinder. Head restraint was provided by ear pads and a bite board. The subject was placed in the restraint in the prone position, and his head was dorsal-flexed about 50°. A cloth shroud, which eliminated motion cues from light and air currents, enclosed the head-end of the cylinder.

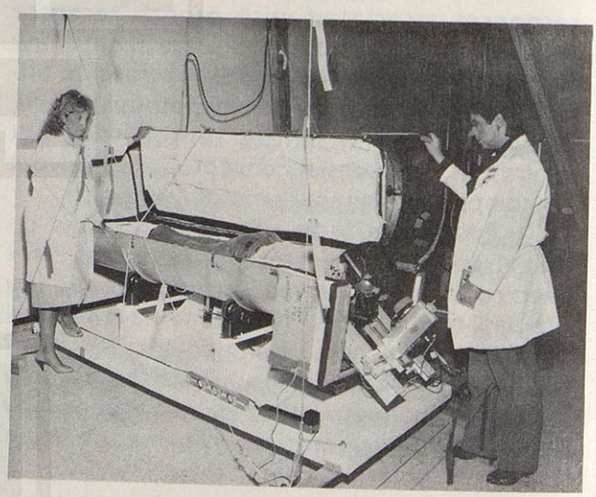

Figure 2. Parallel swing.

PROCEDURE

Responses to three types of motion stimuli were obtained. These were linear translation at 100 cm/s^2 peak; roll at ±5°; and phase-locked, combined roll and linear translation. Translation was in the direction of the subject's Y axis. Roll motion was around the subject's Z body axis (X head axis). For both types of motion, the oscillation frequency was 0.26 Hz.

Three cycles of each type of motion stimulus were presented. The subject's

responses consisted of drawings and verbal reports of his perceived self-motion path.

EYE MOVEMENT RECORDING

SUBJECTS

Two astronauts from one mission participated in this study.

APPARATUS

The apparatus was the same as that used in the self-motion path perception study with the addition of eye movement recording capability. Eye movements were recorded using an experimental RCA infrared video camera. The peak sensitivity of the camera was 890 nanometers. The camera was focused on the subject's left eye with the aid of extender rings. The light source was an array of twelve 100-mw infrared-emitting diodes mounted on the camera lens. The camera output was recorded with a video cassette recorder.

PROCEDURE

Eye movements were recorded during roll ± 15°) and Y axis linear translation oscillation (200 cm/s^2 peak). The oscillation frequency was 0.26 Hz. The goal was to record during five consecutive cycles of movement. The subject's "arousal level" was not controlled.

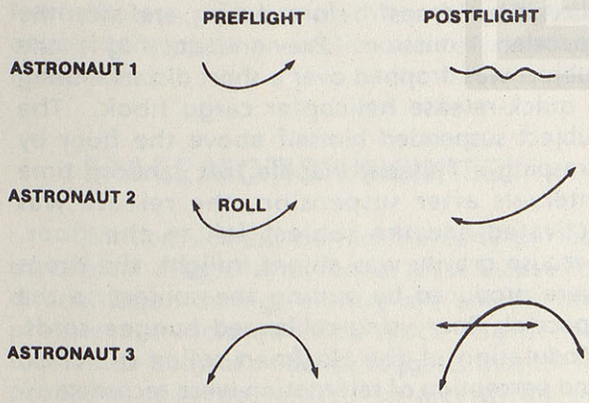

Figure 3. Astronauts' drawings of self-motion perception following roll stimulation.

RESULTS

PERCEIVED SELF-MOTION PATH

Drawings indicating perception of self-motion path during roll are shown in Figure 3. Preflight, the three astronauts reported that cylinder roll produced nearly pure roll self-motion perception, which they illustrated by drawing a "U" shape with arrows at the ends, and that linear translation oscillation produced nearly pure horizontal linear self motion. Immediately postflight, roll stimulation was perceived as translation self motion with a small angular motion component. The verbal reports and drawings were congruent.

EYE MOVEMENTS

Analyzable data during roll oscillation were obtained from both subjects on days 2 and 3 after landing. Fewer usable data were obtained during linear translation.

Because of the poor quality of the video tape records, quantitative analysis focused on transient horizontal eye movements. Horizontal nystagmus during roll stimulation was greater immediately postflight than 2 or 3 days after landing or preflight. The data suggest depression of horizontal eye movements during roll on day 2 after landing and some rebound on day 3. Data obtained during translation stimulation suggest enhancement of the horizontal eye movement response on the second and third day after landing.

Qualitatively, the recording during roll from Astronaut 2 immediately postflight appears different from the other recordings. This record shows the "classic" phase reversing horizontal nystagmus seen ordinarily during oscillation around the Z head axis.

Eye movements were difficult to assess immediately postflight because of the movement of the astronaut's head in the restraint relative to the camera, poor image quality, and the inability of the subjects to maintain straight-ahead gaze.

The video tape records showed a clear ocular counterrolling for Astronaut 3 during roll stimulation. The counterrolling was observable 150 minutes after landing as well as preflight

and on the second and third days after landing. Because of the poor image quality, no attempt was made to analyze counterrolling quantitatively.

CONCLUSIONS

OTOLITH REINTERPRETATION

The results of this experiment support the hypothesis that the brain adapts to prolonged weightlessness by reinterpreting all otolith signals as indicating linear translation. This tilt-translation reinterpretation is reasonable in view of the normal functions of the otolith receptors and analysis of how these functions must change in weightlessness. In weightlessness, no changes in otolith signals are associated with head tilts; only linear translations elicit responses from these receptors. Therefore, it is reasonable to expect that the adaptive brain would learn to interpret all otolith signals as indicating linear translation and that both eye movement reflexes and self-motion perception would be altered accordingly.

Melvill-Jones (9) may have been the first to note that adaptive changes during orbital flight could leave the brain temporarily unresponsive to otolith stimulation by the steady "G" vector. Young, Oman, and their colleagues (10) suggested "otolith reinterpretation" as one of several possible consequences of prolonged weightlessness.

Roll stimulation immediately postflight elicited complex self-motion reports. The self-motion perception included both linear and angular motion components. Also, both horizontal eye deviation and ocular counterrolling were elicited by roll stimulation within the 150-min period after landing. These results are interpreted as follows: Upon return to the normal-gravity environment, the brain persisted in interpreting otolith signals as linear motion. Therefore, the otolith signals produced by roll (tilt) elicited horizontal eye deviation and were perceived as linear motion. Because oscillatory roll also stimulates the semicircular canals, the self-motion path was perceived as a combination of roll and translation, and ocular counterrolling was present.

Results from five other life sciences space experiments are congruent with those reported here. Immediately postflight, astronauts exhibited decreased postural stability with their eyes closed (24), slightly decreased ocular counterrolling during tilt (22), improved ability to null lateral linear motion in the "closed loop otolith nulling task" (24), and unchanged linear oscillation detection thresholds (16, 22). One subject noted that the "rooftop illusion," ordinarily experienced during translation on the U.S. Lab Sled, was absent during the immediate postflight period.

These additional postflight observations are consistent with the otolith tilt-translation reinterpretation hypothesis for the following reasons. Decreased postural stability and ocular counterrolling should be associated with failure to interpret otolith responses following roll stimulation as head tilt. If all otolith signals are interpreted as linear motion, performance of the closed-loop nulling task, which requires precise linear motion detection, should be improved. Because motion detection would be independent of the particular class of motion perceived (translation or tilt), self-motion detection thresholds during linear oscillation should be unchanged. Finally, if all otolith output is interpreted as linear translation, the rooftop illusion (10,13) should be lost.

These observations led Young et al. (24) to propose a tilt-translation reinterpretation hypothesis that is nearly identical to the one developed independently by this study (15,16).

A sixth observation suggests an additional type of otolith reinterpretation. Reschke, Anderson, and Homick (18) examined vestibulospinal reflex and perceptual responses elicited by "drops" before, during, and after the Spacelab 1 mission. Pre- and postflight, the subject was dropped over a short distance using a quick-release helicopter cargo hook. The subject suspended himself above the floor by grasping a T-shaped handle. At random time intervals after suspension, the release was activated and the subject fell to the floor. Because gravity was absent inflight, the drops were produced by pulling the subject to the Spacelab floor using calibrated bungee cords. Modulation of the Hoffman reflex (H-reflex) and perception of self motion were recorded.

During the early period of space flight, sudden drops were perceived as "falls," but by the sixth day of flight the drops were perceived

as linear translations but not as falls. The subjects reported that drops early in the flight felt much as they did preflight. The H-reflex changes associated with these drops also were similar to those recorded preflight. Later in the flight, the drops were perceived as sudden, fast, and hard. The subjects were not aware of where their legs and feet were and exhibited difficulties in maintaining "balance" following "landing." Late in flight, the H-reflex was not potentiated by the drops. Postflight, the drops were perceived just as they were by the sixth day inflight. That is, the subjects were unaware of where their feet were, and the drops were perceived as unexpected and hard (19).

These observations support an otolith reinterpretation hypothesis. Under normal-gravity conditions, a sudden drop is perceived as a "fall" and elicits an otolith-spinal reflex if the body's Z axis is parallel to the gravity vector. Ordinarily, falls are produced by gravity acting on the body mass and the fall is in the direction of the gravity vector. The reflex response prepares the body for the impact deceleration of landing following the fall.

During space flight, a fall, defined as linear translation parallel to gravity, is meaningless because gravity is absent. The "drops" produced on orbit were linear translations but were not falls. Consequently, the adaptive brain learned to interpret all otolith signals as linear translations but not as falls; reflex and perceptual responses ordinarily elicited by falls were lost.

Certainly the data from the space experiments conducted to date are not ideal, and firm conclusions based on observations from only seven subjects are problematic. Nevertheless, converging lines of evidence appear to support an otolith reinterpretation hypothesis.

SPACE MOTION SICKNESS

Motion sickness during the early period of orbital flight and, to a lesser extent, disorientation during re-entry are among the problems associated with space flight. A substantial body of evidence suggests that these problems may be related to alteration of vestibular responses following prolonged weightlessness (4,5).

Sensory conflict appears to be the basic mechanism underlying space motion sickness (5). During the initial period of exposure to weightlessness, signals from the otolith receptors would conflict with those from the semicircular canals and the eyes. Following roll or pitch head motions, movements of the visual scene and signals from the semicircular canals would indicate that the expected head motion had occurred; however, an appropriate signal from the otolith receptors would be lacking. Many astronauts have reported that pitch head motions during the initial period of orbital flight evoke motion sickness symptoms (12,21). These reports support the sensory conflict approach to space motion sickness as well as an otolith tilt-translation reinterpretation hypothesis.

Alteration of otolith receptor response during prolonged weightlessness also could be related to disorientation following return to a normal-gravity environment. In fact, some crewmembers noted horizontal oscillopsia (visual field motion) during head roll motions while in the re-entry phase of flight.

PREFLIGHT PROPHYLACTIC ADAPTATION TRAINING

Based on the otolith tilt-translation reinterpretation hypothesis and the sensory conflict approach to space motion sickness, it is proposed to develop prophylactic adaptation training (PAT) procedures and apparatus for use by astronauts prior to flight. The proposed training is based on the concept that the brain can be forced to "recalibrate" relationships between otolith and visual signals in a manner that would be appropriate to weightlessness. After training, eye movement reflexes, postural muscle reflexes, and self motion experiences in relationship to visual scene movements would be appropriate to the weightlessness-adapted state. It is hypothesized that the training would afford astronauts significant relief from space motion sickness symptoms during the early phase of orbital flight.

BACKGROUND

As noted previously, people adapt to sensory rearrangements such as those produced when they are placed in slowly-rotating rooms (17) or wear optical devices that reverse or invert the visual scene (7,20). Exposure to these sensory rearrangements frequently elicits motion sickness symptoms.

Weightlessness is a form of sensory rearrangement (6,8,13). Because gravity is absent, the vestibular and skin receptor signals elicited by postural orientation and body motion are different from those experienced on earth. Consequently, the relationships between orientation and motion signals from the visual receptors are rearranged with respect to those from the vestibular and skin receptors.

Following adaptation to visual-vestibular sensory rearrangement, vestibular-ocular reflex and self-motion perception response changes indicate neural recalibration of the relationships between visual and vestibular motion signals (1,2,11). These response changes can be used to assess the current state of adaptation and to determine the adequacy of a prophylactic adaptation training protocol.

PROPHYLACTIC ADAPTATION TRAINER

It is proposed to alter, systematically, the relationships between otolith response changes associated with the subject's movements and the visual scene presented to him (14). Relationships between visual scene and subject motion are illustrated in Figure 4. Normally, when the subject's head is rolled toward his left shoulder, the visual scene rotates around the corneal-retinal axis in the direction opposite to the head tilt.

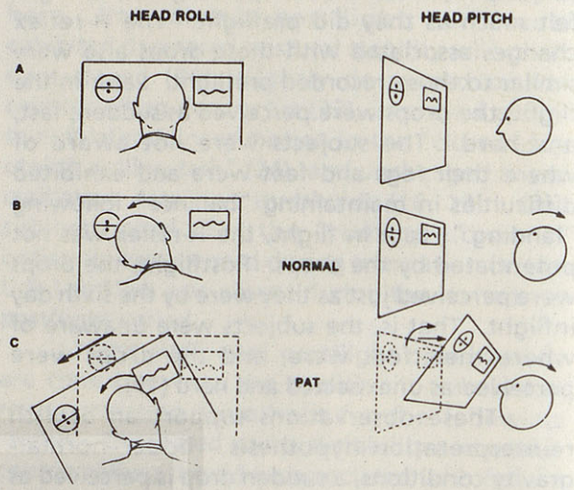

Figure 4. Relationships between head movements and visual scene during PAT.

In the trainer, a leftward head roll would result in a translation of the visual scene toward the left without rotation; i.e., the vertical axis of the scene would remain aligned with the vertical retinal meridian. Normally, when the subject's head is pitched backward, the visual scene moves downward in the visual field. In the trainer, pitch backward would be associated with apparent flow of the visual scene toward the subject, but the horizontal axis of the scene would remain aligned with the horizontal retinal meridian. The relationships between the visual scene and head movements in the trainer would mimic those that are experienced in weightlessness, as revealed by the results of inflight observations.

Several possible concepts for constructing a prophylactic adaptation trainer are currently being pursued.

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