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PULMONARY FUNCTION EVALUATION DURING AND FOLLOWING SKYLAB SPACE FLIGHTS

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ABSTRACT

Previous experience during the Apollo postflight exercise testing indicated no major changes in pulmonary function. Although pulmonary function has been studied in detail following exposure to hypoxic and hyperoxic environments, few studies have dealt with normoxic environments at reduced total pressure as encountered during the Skylab missions.

Forced vital capacity was measured during the preflight and postflight periods of the Skylab 2 mission. Initial in-flight measurements of vital capacity were obtained during the last two weeks of the second manned mission (Skylab 3). Comprehensive pulmonary function screening was accomplished during the Skylab 4 mission. The primary measurements made during Skylab 4 testing included residual volume determination, closing volume, vital capacity, and forced vital capacity and its derivatives. In addition, comprehensive in-flight vital capacity measurements were made during the Skylab 4 mission. Vital capacity was decreased slightly during flight in all Skylab 4 crewmen. No major preflight to postflight changes were observed in the other parameters.

INTRODUCTION

Previous experience during the Apollo Program showed no major changes in pulmonary function when evaluated by postflight exercise testing (1). Although pulmonary function has been studied in detail following exposure to hypoxic and hyperoxic environments, few studies (2, 3, 4, 5, 6) have dealt with normoxic environments at reduced total pressure as encountered during Skylab. The absence of a gravity vector would be expected to facilitate ventilation/perfusion relationships and result in better overall gas exchange in the weightless state. Because of this and the absence in previous history of postflight pulmonary problems, vital capacity was initially proposed as the only functional screening test for Skylab.

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Cardiac output measurements were made in our laboratory (7) during preflight and postflight exercise tests using the technique of Kim *et al.* (8). Due to the magnitude of decreases in cardiac output following the first and second manned Skylab missions and because the method of Kim *et al.* is based upon normal pulmonary function, it was decided to perform more thorough pulmonary function screening in conjunction with the final and longest duration Skylab mission. This paper summarizes pulmonary function data obtained during all three Skylab missions.

METHODS

The Skylab Program consisted of three manned, earth-orbital flights of progessively increased duration (28, 59, and 84 days). Each Skylab crew included a Commander, a Scientist Pilot, and a Pilot. The average composition of the spacecraft gas atmosphere during Skylab was: inspired oxygen partial pressure equal to 170 torr (226 x 10^2 N/m^2), inspired nitrogen partial pressure equal to 75 torr (10 x 10^3 N/m^2), inspired water partial pressure equal to 10 torr (13 x 10^2 N/m^2), and inspired carbon dioxide partial pressure equal to 5 torr (67 x 10^2 N/m^2), although the nominal composition was inspired oxygen partial pressure equal to 181 torr (241 x 10^2 N/m^2) and inspired nitrogen partial pressure equal to 77 torr (103 x 10^2 N/m^2) at a total pressure equal to 258 torr (344 x 10^2 N/m^2). This atmosphere was planned to provide approximate sea level equivalent of alveolar oxygen partial pressure.

The Skylab 4 pulmonary function test equipment layout is shown in figure 1. Skylab metabolic analyzers (9) were used for all Skylab 2 and Skylab 3 pulmonary function studies. Briefly, these units were designed to measure vital capacity and respiratory gas exchange ($\dot{V}_{O_2}$, $\dot{V}_{CO_2}$, $\dot{V}_E$). Each unit had rolling seal spirometers, a mass spectrometer, and an analog computer.

Forced vital capacity and its derivatives were measured during the preflight and postflight periods of the first manned mission (Skylab 2). Initial in-flight measurements of vital capacity were obtained during the last two weeks of the second manned mission (Skylab 3). Comprehensive pulmonary function screening was accomplished during the final manned mission (Skylab 4). One metabolic analyzer was modified to support the Skylab 4 preflight and postflight pulmonary function screening. This unit was modified to compute the volume of nitrogen washed out as: $\dot{V}_{N_2} = (\dot{V}_E \times F_{E_{N_2}} - \dot{V}_I \times F_{I_{N_2}})$.

Oxygen was supplied to the inspiration spirometer via a demand regulator. These modifications permitted residual volume determination by open circuit washout of pulmonary nitrogen during oxygen breathing (10,11,12).

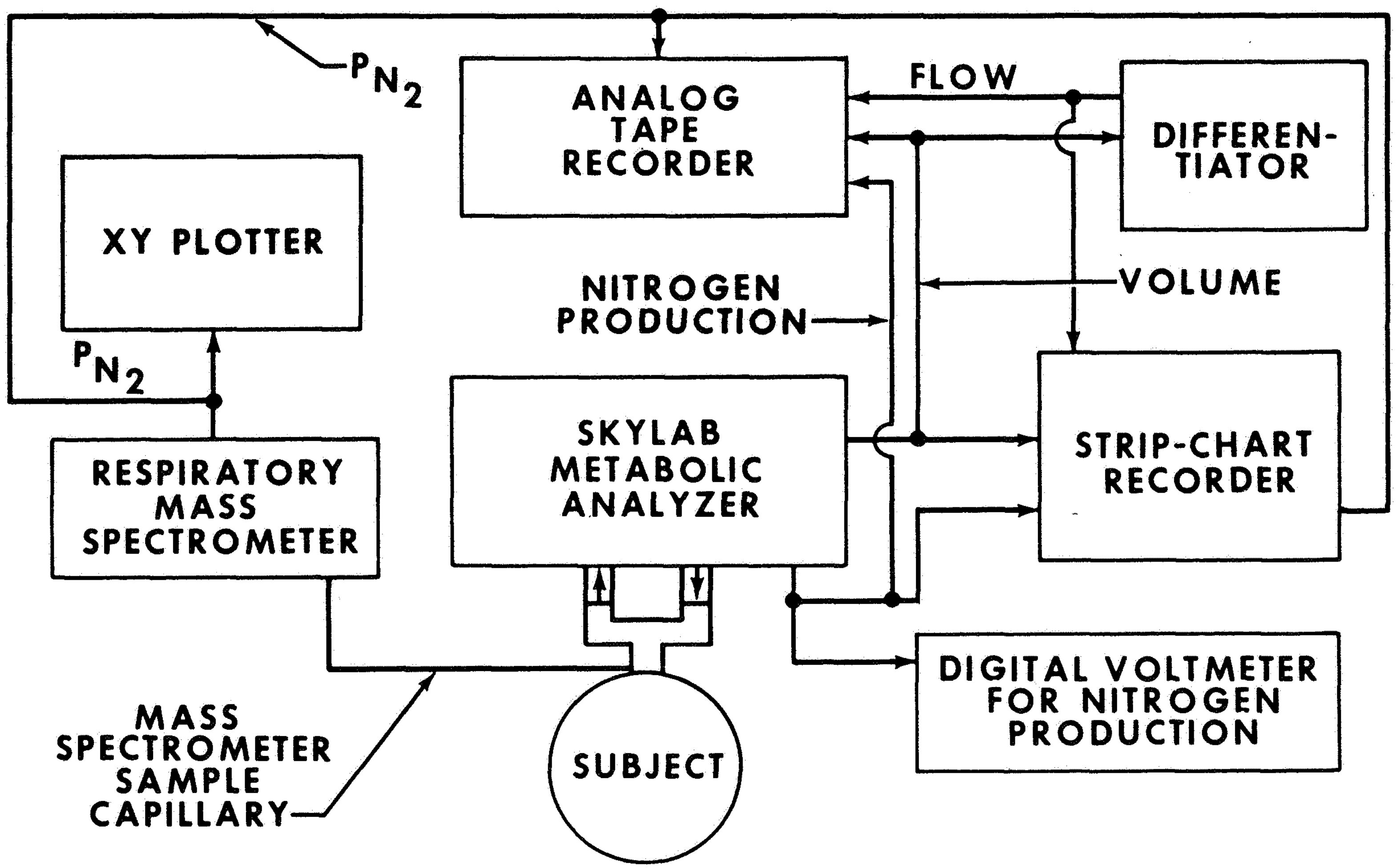


Figure 1. Skylab 4 Pulmonary Function Test Equipment.

A respiratory mass spectrometer monitored nitrogen partial pressure continuously at the subject interface. An XY plotter provided continuous nitrogen partial pressure (ordinate) as a function of time (abscissa) during residual volume determinations.

Closing volume and closing capacity together with their ratios to vital capacity and total lung capacity, have been proposed as indicators of small airway mechanics (13, 14). These indices were computed from data obtained from the single-breath oxygen washout test and residual volume. Vital capacity and forced vital capacity were measured to obtain commonly reported flow and volume parameters (15, 16, 17, 18). Residual volume and closing volume measurements were made with the subject in the sitting position. Vital capacity and forced vital capacity measurements were made with the subject standing.

An analog tape recorder and stripchart were used during all Skylab 4 preflight and postflight testing to provide permanent, synchronous records of nitrogen partial pressure at the mouthpiece, tidal volume, flow rate, and nitrogen washout. The Skylab 4 preflight pulmonary function examinations were conducted five days preflight. Vital capacity was measured at six day intervals in-flight. Complete postflight examinations were conducted on recovery day and 1, 2 and 5 days after recovery. Vital capacity measurements were continued at 11, 17, and 31 days postflight.

RESULTS AND DISCUSSION

Pulmonary function data for Skylab crewmen obtained in the Cardiopulmonary Laboratory at Johnson Space Center during annual astronaut physical examinations are summarized in table I. Vital capacity and flow rate data for the Skylab 3 Scientist Pilot were low relative to reported normal values (16, 18); however, the Scientist Pilot demonstrated adequate pulmonary reserve during numerous bicycle ergometer exercise tests in our laboratory. With the exception of pulmonary function data for the Skylab 2 Scientist Pilot and the Skylab 4 Pilot, table 1 contains the means and standard deviations of data from each crewman's three or four annual physical examinations preceding Skylab.

Skylab 2 Forced Vital Capacity Determinations

Table II summarizes the preflight, recovery day, and first day post recovery forced vital capacity data. No data were obtained for the Scientist Pilot postflight due to orthostatic intolerance complicated by sea sickness. The values shown for each crewman represent the best effort of two trials. The Commander's forced expired volume in 1-second on the first day postflight was significantly reduced. Based on his normal forced vital capacity, it is possible that his decreased forced expiratory volume in 1-second was due to less than maximal subject effort.

TABLE I. PREFLIGHT ANNUAL PHYSICAL EXAMINATION SUMMARIES

	Age (yr)	Height (m)	Weight (kg)	Vital Capacity (liters, BTPS)	Residual Volume (liters, BTPS)	FEV_1 (liters, BTPS)	MMFR 25-75% (liters/sec, BTPS)
Skylab 2							
Commander	43	1.7	62	4.77±0.21	2.18±0.42	3.71±0.14	3.27±0.32
Scientist Pilot	41	1.83	77	6.95*	2.66*	5.07*	4.06*
Pilot	41	1.78	80	5.31±0.09	2.10±0.24	3.94±0.14	3.05±0.11
Skylab 3							
Commander	41	1.75	69	5.03±0.06	2.12±0.25	4.16±0.05	4.34±0.33
Scientist Pilot	42	1.75	62	4.04±0.13	1.54±0.22	3.27±0.04	3.07±0.34
Pilot	37	1.83	89	6.95±0.10	2.02±0.15	5.21±0.18	4.33±0.75
Skylab 4							
Commander	41	1.75	68	6.05±0.21	1.95±0.32	4.65±0.18	4.17±0.25
Scientist Pilot	37	1.75	71	6.26±0.08	1.77±0.01	4.78±0.06	3.93±0.25
Pilot	43	1.75	68	6.30*	1.99*	5.30±0.35	7.43±0.22

All values are mean ±SD with the exception of those with one test only (*). Most values are from annual exams on the preceding 4 years.

BTPS = Body temperature, pressure saturated
FEV_1 - Forced expiratory volume in one second
MMFR = Maximum midexpiratory flow rate

TABLE II. SKYLAB 2 POSTFLIGHT FORCED VITAL CAPACITIES

	FVC(liters,BTPS)			FEV_1 (liters, BTPS)		
	Preflight	Postflight		Preflight	Postflight	
	F-5	R+0	R+1	F-5	R+0	R+1
Commander	4.95	4.74	4.88	3.56	3.57	2.51
Scientist Pilot	7.0	NA	NA	5.02	NA	NA
Pilot	5.28	5.41	5.35	4.03	3.89	4.22

FVC = forced vital capacity in one second
FEV_1 = Forced expiratory volume in one second

F- = Preflight days to launch
R+ = Postflight days after recovery
NA = Not applicable
BTPS = Body temperature, pressure saturated

Skylab 3 Vital Capacity Determinations

In-flight vital capacity measurements were made during the last two weeks of the Skylab 3 mission. Results of preflight, in-flight, and postflight measurments are shown in table III. The Commander showed no changes except a slight increase in vital capacity five days post recovery. Vital capacity of the Scientist Pilot was slightly higher in-flight but normal postflight relative to preflight values. The Pilot exhibited decreased vital capacity in-flight but normal vital capacity postflight relative to preflight.

TABLE III. SKYLAB 3 VITAL CAPACITIES

Vital Capacity (liters, BTPS)

	Preflight*	In-flight			Postflight			
		MD45-47†	MD50-52	MD58	R+1	R+2	R+4	R+5
Commander	5.03±0.06 SD	5.07	4.96	4.87	4.95	-	5.16	5.30
Scientist Pilot	4.04±0.13 SD	4.24	4.36	-	-	3.92	4.11	4.19
Pilot	6.95±0.10 SD	6.10	6.35	6.17	6.91	6.90	6.94	7.01

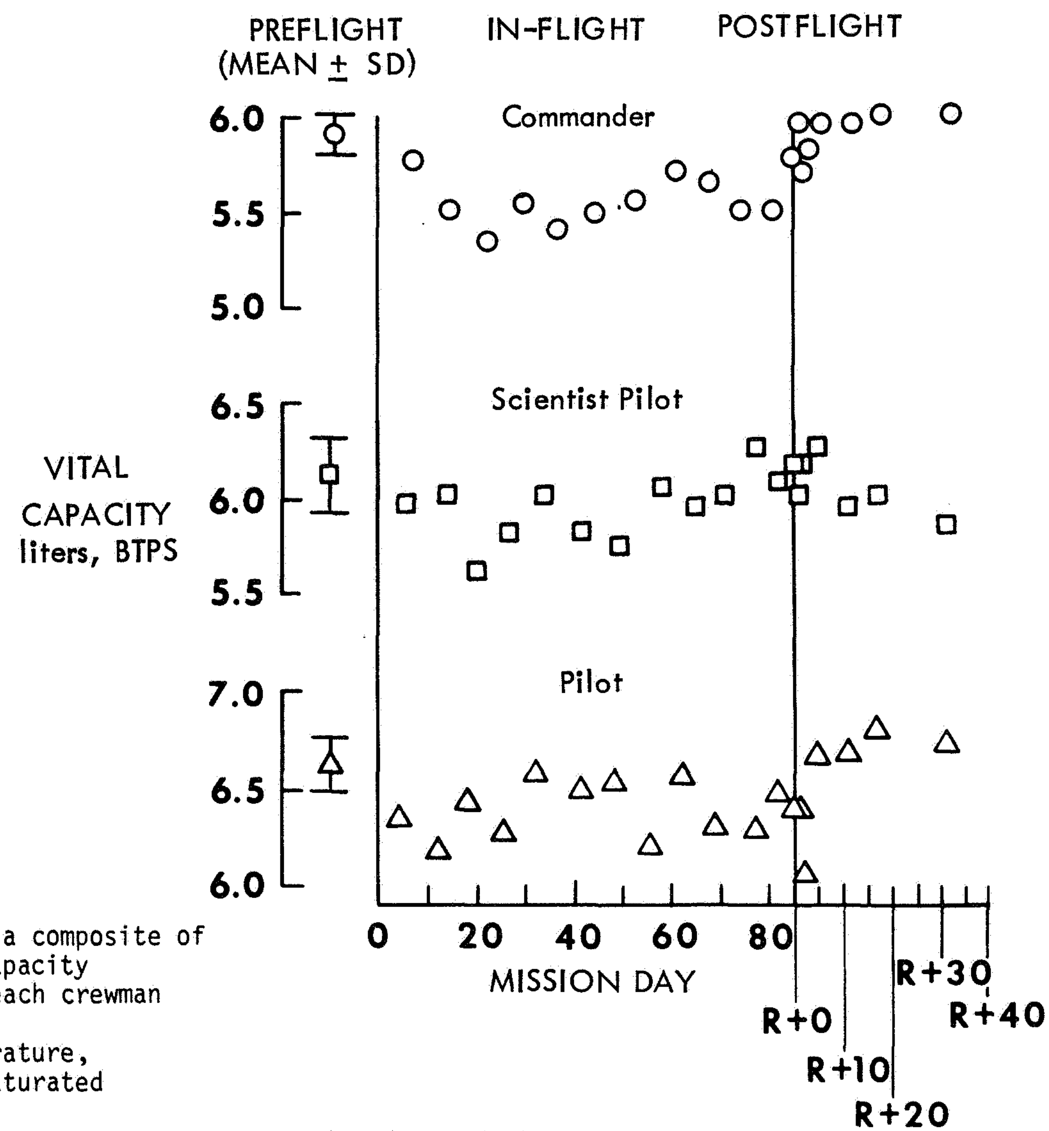
*Data from table I
†MD - Mission Day
BTPS = Body temperature, pressure saturated
SD = Standard deviation

Skylab 4 Vital Capacity Determinations

Vital capacity data for the Commander, Scientist Pilot, and Pilot are shown in figure 2. Vital capacities were generally observed to be lower in-flight relative to preflight. Vital capacity for the Commander remained below preflight for the entire in-flight period. All data presented in figure 2 were obtained using experiment M171 metabolic analyzers.

Skylab 4 Pulmonary Function Screening Tests

Nitrogen washout curves showed no indications of trapping. All washout curves appeared to reflect the anticipated two time constants representing washout of pulmonary and total body nitrogen spaces.



Legend:

Preflight mean is a composite of available vital capacity measurements for each crewman prior to mission.
BTPS = Body temperature, pressure saturated

Figure 2. Skylab 4 vital capacity data.

The Commander had a pronounced vasovagal response following maximal oxygen inspiration during the first closing volume determination on recovery day and further testing was curtailed until the next day. A hardware failure resulted in loss of residual volume measurement for the Commander on the first day following recovery. All other measurements on the first day following recovery, and all measurements on days two and five postflight were within normal ranges. The composite results for Skylab pulmonary function screening tests are presented in table IV.

Residual volume in the Scientist Pilot was slightly increased immediately following recovery and on day two compared to preflight. Residual volume/total lung capacity percent indicated that these changes were probably insignificant. Ventilatory equivalents were variable and reflected the Scientist Pilot's irregular respiratory pattern during washouts.

Although vital capacity for the Pilot was slightly decreased on the second day following recovery relative to preflight, forced vital capacity was normal. Maximum midexpiratory flow rate (between 25 percent and 75 percent of the forced vital capacity) values for the Pilot are the highest recorded in our laboratory for any individual.

Skylab 4 provided the first opportunity for extensive, noninvasive pulmonary function screening on astronauts before and following an extended zero-g exposure. No physiologically significant quantitative decrement in pulmonary function was shown by any crewman during examinations following this 84-day Earth-orbital mission.

Postflight chest films for all crewmen were compared to preflight films to detect changes, if any, in the pulmonary vessels, parenchyma, or heart size. No significant pulmonary vasculature or parenchymal changes were observed in any instance.

Vital capacity, the only parameter measured preflight, in-flight, and postflight, showed in-flight decreases approaching 10 percent in the case of the Skylab 3 Pilot and for the Commander, Scientist Pilot, and Pilot on Skylab 4 (table III and figure 2). These decreases in vital capacity apparently resulted from one or a combination of the following factors:

- cephalad shift of the diaphragm in zero-g,
- body fluid redistribution into the thoracic cavity, or
- a direct result of decreased ambient pressure.

TABLE IV. PULMONARY FUNCTION SCREENING*

PARAMETER	COMMANDER F-5	R+0	R+1	R+2	R+5	SCIENTIST PILOT F-5	R+0	R+1	R+2	R+5	PILOT F-5	R+0	R+1	R+2	R+5
VC (liters)	5.83	5.94	5.72	5.82	5.94	6.11	6.16	6.00	6.16	6.26	6.49	6.38	6.38	6.05	6.64
RV (liters)	1.40	1.53	- -	1.31	1.43	1.53	2.18	1.27	2.43	1.65	2.20	1.67	2.00	2.20	1.53
TLC (liters)	7.23	7.47	- -	7.13	7.37	7.64	8.28	7.27	8.59	7.92	8.69	8.05	8.38	8.24	8.17
RV/TLC (%)	20	21	- -	18	19	20	26	18	28	21	26	21	24	27	19
TV (liters/breath)	1.07	1.20	1.00	1.15	0.92	2.48	2.83	1.87	- -	1.48	2.23	0.92	0.94	0.82	0.80
V_A/RV	30	23	- -	33	16	48	28	48	27	16	23	21	17	18	16
FVC (liters)	5.61	- -	5.56	5.71	6.05	5.83	5.77	5.39	5.88	6.21	6.22	6.22	5.72	6.27	6.32
FVC/VC (%)	99	- -	97	98	102	96	94	90	96	99	96	97	90	104	95
FEV_1 (liters/sec)	4.62	- -	4.29	4.59	4.70	4.35	4.61	4.24	4.37	4.54	5.50	5.50	5.39	5.49	5.29
$MMFR_{25-75}$ (l/sec)	4.32	- -	4.30	4.39	4.14	3.17	5.15	3.69	3.43	3.65	6.61	7.06	7.73	6.82	5.10
MET (sec)	0.65	- -	0.64	0.65	0.73	0.92	0.56	0.73	0.86	0.85	0.47	0.44	0.37	0.46	0.62
MEFR (liters/sec)	12.4	- -	12.0	12.4	12.3	10.5	11.0	10.5	10.9	10.8	11.6	11.6	11.0	12.2	11.4
V (60% TLC) (l/sec)	4.74	- -	3.88	4.61	5.50	3.70	4.74	3.67	3.73	4.87	7.76	7.55	7.33	7.46	5.72
CV (liters)	0.80	0.88	0.83	0.56	0.76	1.02	0.99	0.99	0.49	0.81	0.72	0.89	0.50	0.45	0.59
CC (liters)	2.20	2.41	- -	1.87	2.18	2.55	3.18	2.26	2.92	2.46	2.91	2.56	3.43	2.64	2.12
CV/VC (%)	14	15	16	10	13	17	16	17	8	13	11	14	8	7	9
CC/TLC (%)	30	32	- -	28	30	33	38	31	34	31	34	32	32	33	25

*A summary of measured and derived values obtained 5 days preflight (F-5), immediately following recovery (R+0), 1 day (R+1), 2 days (R+2) and 5 days (R+5) following recovery.
All volume and flow measurements are reported at BTPS conditions.

VC = Vital capacity
RV = Residual volume
TLC = Total lung capacity
V_A/RV = Ventilatory equivalents
FVC = Forced vital capacity
FEV_1 = Forced expiratory volume in 1 second

MMFR = Maximum midexpiratory flow rate
MET = Midexpiratory time
MEFR = Midexpiratory flow rate
CV = Closing volume
CC = Closing capacity

KEY;
CDR=Commander
SPT=Scientest Pilot
PLT=Pilot

Foley and Tomashefski (2) showed a decrease in flow rate with no significant decrease in forced vital capacity when performed during the zero-g portion of Keplerian maneuvers in KC-135 aircraft. Ulvedal *et al.* (6) showed forced vital capacity to be reduced 3 to 8 percent by exposure to equivalent 18 to 33 500 foot altitudes without concomitant hypoxia. Robertson and McRae (4) similarly observed a 4 percent decrease in forced vital capacity in subjects exposed to a 5 psia, oxygen-helium gaseous environment with inspired oxygen partial pressure of 175 torr (233 x 10^2 N/m^2) for a period of 56 days. Vital capacities returned to normal upon chamber descent to near sea level ambient pressure. Vital capacities were measured during Skylab Medical Experiments Altitude Test (SMEAT) (5), a ground-based 56-day simulated Skylab mission in which the environment was comparable to Skylab with the important exception of the presence of Earth's gravity. A standard vitalometer was used for both the pre-altitude and the 5 psia measurements. Mean vital capacity values for the SMEAT Commander, Scientist Pilot, and Pilot were decreased by -4.5, -2.9, and -4.9 percent, respectively, during this 56-day exposure to barometric pressure equivalent to a 27 000 foot altitude without hypoxia. Post SMEAT, vital capacities returned to baseline values. Our in-flight Skylab data are in general agreement with all reported studies (4, 5, 6).

CONCLUSIONS

In summary, the vital capacity changes observed in-flight may be partially explained as a response to 5 psia ambient pressure. However, the proportion of vital capacity decreases directly attributable to other factors such as body fluid shifts and a cephalad shift of the diaphragm cannot be determined from the present data. Regardless of the cause(s) of decreased in-flight vital capacities, a review of post-flight data shows that these changes revert to normal within two hours following recovery without significant impact on crew health status.

Further in-flight comprehensive pulmonary function testing will be necessary during future manned missions in order to substantiate observed decreases in vital capacity and increase our knowledge concerning the physiological effects of the weightless state upon the human body. The Space Shuttle will have a sea level equivalent atmosphere. Therefore, it will provide the first opportunity to evaluate pulmonary function where the primary environmental change will be the weightless state (zero-g).

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