PHYSIOLOGICAL MASS MEASUREMENTS ON SKYLAB

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I would like to thank you for this opportunity of telling you about our medical experiments on Skylab, the things we discovered, and a few we did not. Many of you in the audience have worked directly or indirectly on these experiments and made these results possible.

Some of us and some of you have waited quite awhile for these results; in the case of this experiment almost 8 years. Nine years ago while working on the Air Force's Manned Orbiting Laboratory Project at the Aerospace Medical Division, we concluded that one of the first priorities in space medical research was determination of the cause and time course of the weight loss which always seemed to accompany space-flight.

It was obvious to us and many others that a carefully controlled intake/output study with accurate daily mass measurements in flight would be required. At that time the insurmountable problem to such a study was the lack of an instrument for nongravimetric mass measurement. The first priority, then, was development of a mass measurement which did not depend on weight, and this was started. By 1966 I had built prototypes of the instruments flown on Skylab.

As time went on, the MOL program had an unfortunate end; we had mass measuring devices; NASA had a planned in-flight balance study without mass measuring device, so we formed a joint effort which was implemented on Skylab. This morning I will describe the methods used to measure mass in weightlessness since this technique has not been used before, and then--as time allows--discuss the results obtained, results which affect both many other experiments and future planning.

Gravimetric mass determination or weighing is such a simple and accurate process that no other methods have been developed or really needed since the Egyptians began using balances 5000 or more years ago. The only practical alternative to gravimetric attraction is some determination of the mass' inertial property. The method chosen to do this in 1965, and not necessarily the present method of choice, was the spring-mass oscillator constrained to linear motion.

Slide 1-1

This is a schematic of the method. A sample mass is placed between two springs and constrained to linear motion in the longitudinal axes of the springs. If the mass is displaced from its rest position X_0 to a new position X and released, it will undergo essentially undamped natural oscillation at a frequency given by the well-known relationship shown.

If this period of oscillation is accurately measured by a high resolution timer, mass may be calculated. Rather than attempt a calculation based on machine quantities such as spring rates, a calibration which would have inevitable errors from gravitational effects, an in-flight calibration using precision masses is done.

Slide 1-2

This plot is from one of the small or specimen mass measuring devices used on Skylab and simply shows that it follows the theoretical curve reasonably well. With care and by using a modified calibration curve, accuracy of .01 percent, or better, can be obtained with solid masses. This system is, of course, sensitive to any (slosh) nonrigidity in either sample or mounting and to (jitter) any external or sample oscillation if either of these effects are near the fundamental frequency of oscillation. Thus, in the case of some food, liquids, and the human body, special arrangements must be made.

Let me describe these arrangements and the in-flight operation by showing you a film of the hardware that was flown on Skylab.

FILM NARRATION

This film was made in the Skylab crew trainer which is as close as possible to the in-flight arrangement. Two small instruments of 1 kilogram capacity were flown--one in the wardroom which I'm now entering. All food was carefully weighed, analyzed, and identified preflight. Any package which was not totally consumed, and only six or so out of the thousands were not, was placed in the device shown here, and measured.

This is the oscillating specimen tray, and the perforated elastic sheet holds the food package to it. Operation consists of turning the counter on, zeroing it, and rotating and holding the lever which successively unlocks, displaces, and then releases the specimen tray. The time for three periods of oscillation is then registered by the opto-electronic counter to 10 μ seconds. This time was recorded and voice relayed to Earth where mass was calculated and suitable adjustments made to the next day's meals.

Now moving on to the head, there is a second and identical instrument on which all vomitus, of which there was only 3-4 samples, and all feces were collected, in such bags, and measured. An on-board graphic conversion to mass was made to allow proper setting of the fecal drying timers. All fecal samples were dried and returned to Earth in toto for analysis with the oscillation time periods.

Here, we have the large or body mass measuring device with 100 kilograms capacity. A basal body mass was made by each crewman every morning after arising and voiding. The same type of clothing of known mass was worn each day and any extra objects removed from the pockets. Although the human body is supposed to move as a single rigid structure below one cycle per second, this proved to be only approximately true; and it was necessary to reduce slosh to a minimum by folding the body into the most rigid configuration possible, as you see here, and to reduce the period of one cycle of oscillation to 2 seconds. Straps are necessary under weightlessness to constrain the body to the seat.

The same timer and timing arrangement is used as on the small devices. After strapping in the seat is unlocked and cocked by the large handle. The timer is turned on, zeroed--one takes a breath--holds it to avoid "jitter" and then releases the seat to oscillate by means of a trigger on the hand bar. After three cycles of timing are complete the period is recorded and returned to Earth where mass was calculated.

Slide 1-3

This is a record of the total uncorrected deviations of the specimen mass measuring device in the head at the 50-gram calibration point. These points were taken over three missions as shown. Without going further into the engineering aspects, maximum error for food and vomitus samples was less than 3 grams. Repeatability of body mass measurements was ±0.1 pounds, and absolute accuracy was between +1/4 and +1.0 pounds and probably nearer +1/4 pounds.

A number of hardware support measurements were made during the mission with excellent results. For example, 24-hour urine samples to ML. Until Skylab there was an unexplained loss of weight on every American, and so far as I know, Russian flight and in every astronaut except Alan Shepard on Apollo 14.

There were three common theories to account for these losses:

1. Under weightlessness fluid was shifted from the lower portions of the body to the chest area where it was sensed as an excess and secreted by the kidneys in accord with the Gauer-Henry theory.

2. At least a portion of the loss was sometimes thought to be metabolic since food quantities and opportunities to eat were frequently minimal.

3. Under certain conditions there were periods of high physical activity with heat and other stresses which resulted in rapid loss.

A comment may be in order:

One often thinks of daily weights as a highly variable measurement--as indeed they are unless carefully made. But if they are carefully made under basal conditions and if the subject is on a controlled diet, losses of a fraction of a pound per week become not only detectable but significant. While a few ounces per week loss or gain is normally of no importance, if they are continued for months, especially under conditions which can't be altered, they become significant indeed.

The slides I will now show are plots of Skylab crew body weight--preflight and postflight from experiment M-071 and in-flight equivalent weights from the body mass measurement device. The data has been smoothed by taking a 3-day sliding average. It covers the period that the crew was on the Skylab diet.

Slides 1-4 and 1-5

These plots are from the commander and pilot of Skylab 2. The science pilot had a similar curve with a total loss between the two shown. The first few days' data was lost during vehicle repairs, and this was also a period of heat stress. One sees a loss which began with the diet and accelerated during the mission itself. The sharp dip in flight was coincident with EVA. Immediately postflight there was a transient increase in weight followed by a plateau. The predominant loss pattern of the first flight is consistent with a simple metabolic deficit.

While the losses were easily sustained in this short mission they could not be tolerated on missions of long duration. Even the 3 1/2 pound loss of the commander is significant in a small crewman who launched with a body fat of less than 10 percent.

Slides 1-6 and 1-7

On Skylab 3 both food and exercise were increased, and we see a different pattern. The commander was relatively stable preflight, had a sharp loss for the first few days in flight, and another loss near the end. On recovery there was the usual increase and plateau or inflection point. The pilot, whose data is not shown, had an almost identical curve. Remember that all crewmen had nausea and were not eating properly the first few days and that there is a period of increased activity, especially for the pilot and commander prior to reentry. The science pilot had a sharp loss on exposure to weightlessness and a small continued loss in flight consistent with a metabolic deficit and a typical recovery pattern. Here, I feel that we see two other loss mechanisms demonstrated.

From the time course of the losses and gains on orbital insertion and recovery, it seems reasonable to conclude that fluids are involved. This will be discussed further in a moment. At the same time, there are periods of increased stress, such as preparation for reentry or EVA on Skylab 2 which temporarily exceed caloric intake.

Slide 1-8

On Skylab 4 food and exercise was again increased, and we have the second American in space who lost essentially no body mass in flight--the commander. His profile shows a preflight gain, a small initial loss, and postflight gain. His crewmen had losses similar to but smaller than Skylab 3.

At this point, we seem to have come full circle and have demonstrated that all three mechanisms originally proposed are operative. It would appear that the most significant on this mission was a simple metabolic loss. In further support of this, the average weight loss of all crewmen was plotted versus the normalized average caloric intake. The caloric data shown is the latest obtainable from the food section.

Slide 1-9

Although the sample is small, the relationship seems clear, the three subjects of the "main line" relation were also the three crewmen with the smallest body fat--all three under 10 percent.

Caloric intake required for an extrapolated zero loss is extremely high indicating a surprisingly high in-flight metabolic cost.

It must be recognized that simply adding food to the diet is not the answer, for while this will assuage hunger and maintain mass, body muscle might be exchanged for fat. This closely related problem of exercise and conditioning will be discussed next.

Slides 1-11 and 1-10

These plots are 2-day sliding averages of crew mass from Skylab 3 and 4 for 10 days following insertion and recovery to demonstrate fluid losses. On Skylab 3 there was a sharp loss of 3-4 percent of body weight over the first 4 or 5 days following exposure to weightlessness. On return to one-g there was an approximately reciprocal gain. On Skylab 4 we see the same pattern in one crewman--the crewman who was nauseated and not eating and drinking, just as had been the case with all three Skylab 3 crewmen. The other two crewmen show a much less pronounced drop, and on recovery there was a smaller reciprocal gain except for the science pilot. It is my suspicion that transient fluid losses or gains will be small, probably on the order of 1 percent in crewmen who eat and drink adequate amounts throughout the mission. This intriguing question of fluid loss and the Gauer-Henry theory will undoubtedly be further addressed by the appropriate investigators to show routes and mechanism of loss and gain.

For the future, dietary standards must be revised to meet the metabolic requirements of given missions and tasks. In-flight studies of metabolic costs of realistic activities will allow better definition of overall requirements.

To those of you concerned with future planning; as long as man flies and measures in flight, he will continue to need mass measurements. Although the present system met the requirements, they were complex, heavy, and expensive. I trust that they will not become the accepted standard, for in the 8 years since development of these devices, I have devised a number of others with marked advantages over the spring-mass oscillator.

In summary, we have demonstrated a new instrument for in-flight space operations and research, have demonstrated the previously unproven mechanisms of weight losses under weightlessness, and most importantly, helped to prove that the human body properly fed can sustain missions of long duration without significant obligatory mass loss.