Observations on Heart Rate and Cardiodynamics During Weightlessness

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OF ALL THE physiologic processes which are affected by the zero-gravity state, the activity of the heart has attained by far the greatest attention. The reason for this fact may be sought in the general importance which this organ system complex has with respect to health and survival. Moreover, so it at least appears, the cardiovascular activities are primarily based on mechanical principles; and therefore it seems hardly possible that the heart should function properly and independently of gravity and weight-free states.

AIR FORCE STUDY

In 1951, Henry, Ballinger, Maher, and Simons[6] conducted experiments on pulse rate and electrocardiogram of animals and man during subgravity states. For studying seven slightly anaesthetized primates during short flights in V-2 and Aerobee rockets, the ECGs were recorded from needle electrodes in the leg and chest.[7] Venous and arterial cannulae of polyethylene tubing were connected to Statham pressure transducers. Frequency modulated signals were telemetered and recorded oscillographically.

The flight pattern of the rockets included accelerations of 4-5 g with the V-2 and a three-minute free flight period approximating the zero-G condition very closely. In the Aerobee there was a 2.5-second initial impulse of 15 g and a steady 45-second thrust with a peak acceleration of 3-4 g. Then a subgravity state of less than 1/10 G existed for the remainder of the free flight. Pulse and respiratory rates obtained on the first four animals are summarized in Table I. The variations from control values were transient and probably not significant. There were also some episodes of breath holding during the high accelerations and shortly thereafter; and this also occurred with two monkeys flown later in Aerobee III.

Data on arterial pressure recorded in Aerobee II reveal that there was a slight rise from 113/80 to 130/100 mm. Hg during liftoff. Then the pressure decreased until the parachute opened. Changes in venous pressure are small. There was no sharp rise which would indicate breath holding or struggling. However, the short series of minor changes from 10 cm. to 27 cm. H_2O during parachute shock may have been associated with brief breath holding as well as other factors, including an artifact.

The respiratory rates and ECGs taken twenty-five seconds before liftoff in a V-2 were previously published in

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this journal.[6] The chest and leg leads and recording system employed resulted in an inverted T wave in the resting state. At X $^{+}200$, that is, during zero-G, neither respiration nor the ECG showed significant change.

TABLE I. ANIMAL STUDIES OF THE SUBGRAVITY STATE

Pulse and respiratory rates of narcotized monkeys during a control period, powered ascent, exposure to subgravity and subsequent free fall or parachute spoiled descent; showing the absence of any gross disturbance during the period of zero gravity (Henry et al).

	Pulse Rate Per Minute				Respiration Per Minute			
	Control	Powered Ascent	Sub-gravity	Free Fall	Control	Powered Ascent	Sub-gravity	Free Fall
Approx. time in seconds		0-50	50-200	200-400		0-50	50-200	200-400
Acceleration	1g	4-6g	0.1g	1g	1g	4-6g	0.1g	1g
Expt. No. V_2a	190	110	190-180	—	90	60	65-60	—
V_2b	190	200	210-200	200	40	50	60-50	
Aerobee I	210	220	190-185	220	60	65	60-20	60
Aerobee II	166	172	178-178	175				
Mean	190	175	190-185	205	60	60	60-40	60

In Ballinger's experiments with men in a modified F-80E aircraft, both the pilot and passenger were instrumented to obtain an ECG during subgravity periods.[1] During each flight the subject experienced eight of ten periods of subgravity ranging from fifteen to twenty seconds. There were no significant alterations in heart rate or the ECG during the weightless states.

WEIGHTLESSNESS STUDIES IN THE USSR

Bioastronautical studies in the USSR included a series of experiments in hermetically sealed capsules involving nine dogs, three of which were used in two flights.[3,8,11,18] In the second series twelve dogs were exposed to weightlessness for about 3.7 minutes. Six animals were launched twice. Cabin pressure and temperature, respiratory rate, arterial blood pressure, and heart rate were telemetered. The findings are summarized in Table II. Systolic blood pressure varied in the basal or prelaunch state from 120 to 150 mm. Hg and the diastolic from 60 to 70 mm. Hg. During liftoff the systolic pressure rose about 60-70 mm., and the diastolic, 10-12 mm. Hg. In one animal the pressure did not change. The arterial pressure declined slightly in the subsequent period of weightlessness, about 10-15 mm. Hg, but no consistent pattern of change was found during free-fall and re-entry.

Pulse rate during the pre-flight period usually varied from 95-160 beats per minute. Both an increase and a decrease in pulse rate were observed during the burning stage. In most instances it increased about 32-56 beats per minute; in one animal it remained unchanged; and in three animals it decreased 6-60 beats.

Heart rate remained essentially unchanged during weightlessness, except for a slight decrease in frequency. In eight out of ten animals the rate decreased 7-24 beats; and in two dogs the decrease was 36-46 beats per minute.

At the end of the cruising state the nose cone was separated by an addi-

TABLE II. EFFECTS OF ACCELERATION AND WEIGHTLESSNESS ON 12 DOGS DURING ROCKET FLIGHT
(After A. V. Prokrovski, USSR)

	Normal Conditions	Acceleration	Weightlessness
Blood pressure Systolic Diastolic	120-135 mm. Hg 60- 70 mm. Hg	180-205 mm. Hg 70- 82 mm. Hg	Arterial pressure usually dropped 10-15 mm. Hg
Heart rate	95-160 mm. Hg	Most cases increased 32-56 beats/minute; One (1) case unaltered; Three (3) cases dropped 6-60 beats	Eight (8) cases decrease 7-24 beats; Two (2) cases drop 36-46 beats; in one (1) case increase of 25 beats/minute
Respiration rate	30-52 per min.	Majority unchanged; Decrease in one (1) case from 156 to 66 per minute, in another case decrease 52-28 per minute	Decrease not exceeding 6-17 per minute

tional booster. This produced only a slight increase in pulse rate in two animals. During the free-fall period pulse rate declined 8-24 beats in ten dogs, remained unchanged in two dogs, and increased 25 beats in one. None of these changes were considered abnormal, since changes in the electrical axis, of the QRS complex, reversal of the T wave and other alterations were observed under resting conditions.

During acceleration at liftoff, the time course of the respiratory rate of most animals was practically unchanged. However, in one dog it decreased from 156 to 66, and in another, from 52 to 28. Generally, a moderate drop was noted during weightlessness which was statistically within the normal variations observed. Data on pulse and respiratory rate of four animals are shown in Figure 1.

Data obtained from Laika in Sputnik II showed that during liftoff the frequency of the heart beat rose to a rate about three times that of her basic rate. Later on, when acceleration reached maximum, the rate diminished. Upon reaching the zero-G state, the pulse spiked transiently and slowly returned to normal. Analysis of the ECG revealed changes in the configuration of the various complexes and duration of the intervals. The changes were not abnormal but indicative of increased rate of activity during acceleration. In the subsequent period of weightlessness these manifestations returned to the prelaunch cardiodynamic and respiratory state, indicating that zero-G did not produce permanent alterations in the physiological conditions of the animal.

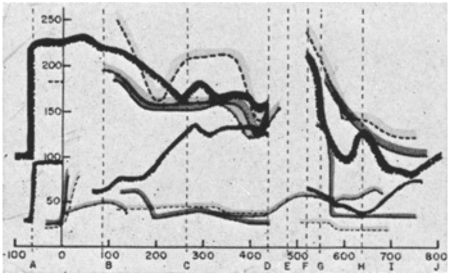

Fig. 1. Pulse and respiration of four non-anesthetized dogs. A. Instruments turned on; B. Moment of launching; C. Engine turned off (beginning of weightless period); D. Detachment of rocket nose cone; E. Entry into the dense layers of the atmosphere (end of the weightless period); F. Period of even motion of the nose cone; G. and H. Moments of parachute openings; I. Moment of landing. (After A. M. Galkin, et al.).

EXPERIMENTS ON THE "SUBGRAVITY TOWER"

At the "Centro Studi e Ricerche di

Medicina Aeronautica" in Rome, Italy, Lomonaco and his scientific staff used a rather simple device to study the effects of acceleration and subgravity.[9,10] The "Subgravity Tower" consists of metal framework about 40 feet high, within which a platform is suspended by means of elastic ropes. Upon sudden release, it moves up and down producing accelerations varying from 3 to zero-G.

A complete ECG with peripheral and precordial leads was recorded from ten subjects in a supine position during the changing accelerations. The ECG showed an increase in cardiac rate. For four men with normal initial rate the maximum increase was greater (+41 per cent) than that observed on six subjects with initial tachycardia (+27 per cent). When the platform was stopped, heart rate assumed its normal value. An inspection of individual records did not show a close relationship between motion and cardiac rate. However, considerable variations in frequency were found during the one-minute period that followed the exposure.

Moreover, the ECG complexes showed slight variations similar to those produced by minor rotations of the electrical axis. They were interpreted by Lomonaco et al as symptoms of individual cardiac motility. It is highly probable that the effect of the brief apnea observed during the experiment, the emotional factors involved, and the stresses induced by abruptly changing accelerations were more instrumental in producing the symptoms described above than the relative short periods of subgravity and zero-G.

POST- AND PRE-ACCELERATION WEIGHTLESSNESS STUDIES

Effects of acceleration and weightlessness were investigated in several experiments by von Beckh.[14-16] After an acceleration of 4 to 6.5 g lasting for about 40 seconds, produced by the pilot of a jet aircraft in a "diving spiral," subgravity was obtained for about 40 seconds. The post-acceleration weightlessness pattern, simulating the conditions after burnout, was started with a high G-load and followed by a subgravity trajectory. The pre-acceleration weightlessness time course had the weightless period immediately followed by a state of increased acceleration. The time course of acceleration and of a typical heart rate pattern were given in an earlier report by von Beckh (1959).[16] The essential results are the increase in heart rate and its fluctuations for an extended part of the post-acceleration period, and the lower heart rate during subgravity and its slower increase in the high G-period during pre-acceleration weightlessness, which resembles re-entry conditions. Subjects reported the most severe effects in the latter state, when the weightless situation was followed by a marked increase in weight. The experience of discomfort, substernal pain, and visual impairment was less pronounced during post-acceleration weightlessness, but the time for the normalization of heart rate was extended.

PROJECT MIA

A series of experiments on the heart rate of rodents was conducted by van der Wal and Young, resulting in the "Mouse-in-Able" study early in 1958.[13]

Three rockets were flown each of which carried an animal; but none of them was recovered. Only the second and third mouse were instrumented. On the other hand, heart rate in the other mouse slowed during powered flight but increased slightly during weightlessness.

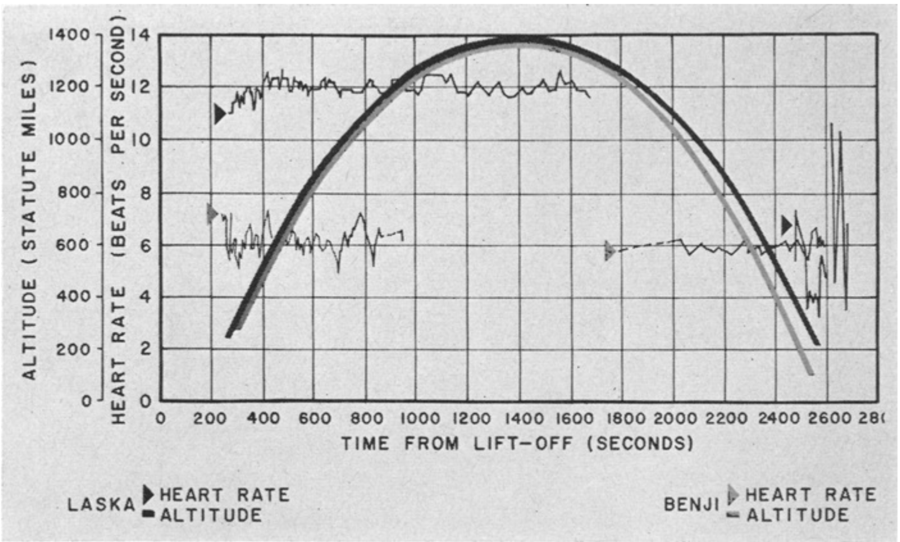

Fig. 2. Heart rate and altitude during weightlessness. Thor-Able Rockets Numbers 2 and 3.

Heart rates of the animals during weightlessness are shown in Figure 2, which also contains a schematic representation of the flight profiles. The records obtained differ considerably with regard to their manifestations as well as to the duration of coverage by the various ground stations.

Under resting pre-launch conditions, the heart rate for one of the mice was about 12 beats per second and for the other 5.2 per second. Moreover, the animals responded quite differently to the effects of flight. One showed an increase in heart rate during the periods of high acceleration and shortly after the first stage burned out, but no tachycardia during the period of post-acceleration weightlessness. On the other hand, heart rate in the other mouse slowed during powered flight but increased slightly during weightlessness.

Finally, the effects of the high G-load during re-entry were considerable. After having dropped to an average of about 5 beats per second shortly before re-entry, it increased to 12 while the animal experienced about 60 G; and it fluctuated very much during the deceleration phase, in which strong vibration, buffeting, and shocks usually occur.

THE ARMY-NAVY STUDY

On December 13, 1958, a South American squirrel monkey ("Old Reliable"), and on May 28, 1959, a 6-pound rhesus ("Able") and a squirrel monkey ("Baker") were launched from Cape Canaveral, Florida, in the nose cones of JUPITER

IRBMs. Although the first animal was not retrieved, its ECG, respiration rate, heart sound, and body temperature were telemetered in flight. The other two animals were recovered.

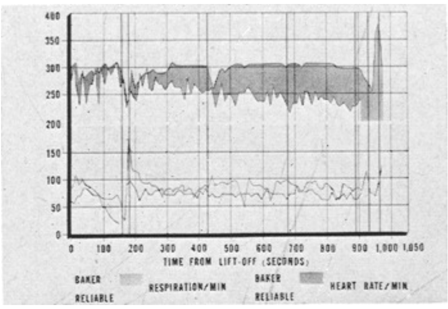

Fig. 3. Heart rate and respiration of two squirrel monkeys ("Old Reliable" and "Baker") during flights in Jupiter Missiles AM-13 and AM-18. The values are the means of ten-second intervals.

The time courses of cardiac and respiratory rates of the two squirrel monkeys are summarized by Figure 3. It can be seen that the noise of the engine at liftoff startled the animals and immediately produced an increase in their heart rates. Respiratory rates also increased briefly, but slowed later with the increment of acceleration. Heart rates fluctuated considerably, but by and large showed an upward tendency during the greater part of the launch period and then, like that of Laika, decreased suddenly, despite continued and increased acceleration. About 15 G was experienced during powered flight.

The period of free flight and weightlessness was essentially uneventful. Baker's cardiac rate averaged its basal values (about 300); whereas Old Reliable's rate fell below its base line figure (276) to 240 beats per minute. Within two seconds after burnout, Baker's heart rate rose sharply but then returned to values not much above those observed during the prelaunch period. While Baker's heart rate remained relatively constant during the free-flight period, in which the nose cone tumbled slowly, producing an acceleration of about 0.03 g, that of Old Reliable decreased markedly even during the period of spin-up, at which time the animal experienced about 0.3 G. Slight changes in the RST segment and T waves were also noted, which were not considered pathological, and transient in nature.

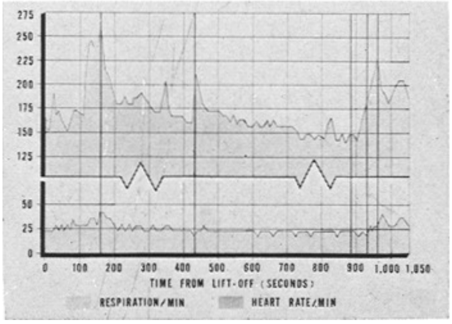

Fig. 4. Heart rate and respiration of a Rhesus monkey "Able" during flight in Jupiter Missile AM-18. The values are means of ten-second intervals.

Figure 4 summarizes Able's cardiac and respiratory rates. After an initial startle reaction shortly after engine ignition heart rate decreased and then increased steeply reaching a maximum of 259 during the 10-second interval at peak acceleration. Respiration increased but slightly throughout the launching phase. There was a period of "tachycardia" during post-acceleration weightlessness; then the heart rate declined steadily and was disturbed only by several startling missile events.

At the end of the subgravity period, Able's cardiac rate was slightly below its basal values. Spin-up, which occurred earlier this time, activated the cardiac and respiratory rates but temporarily.

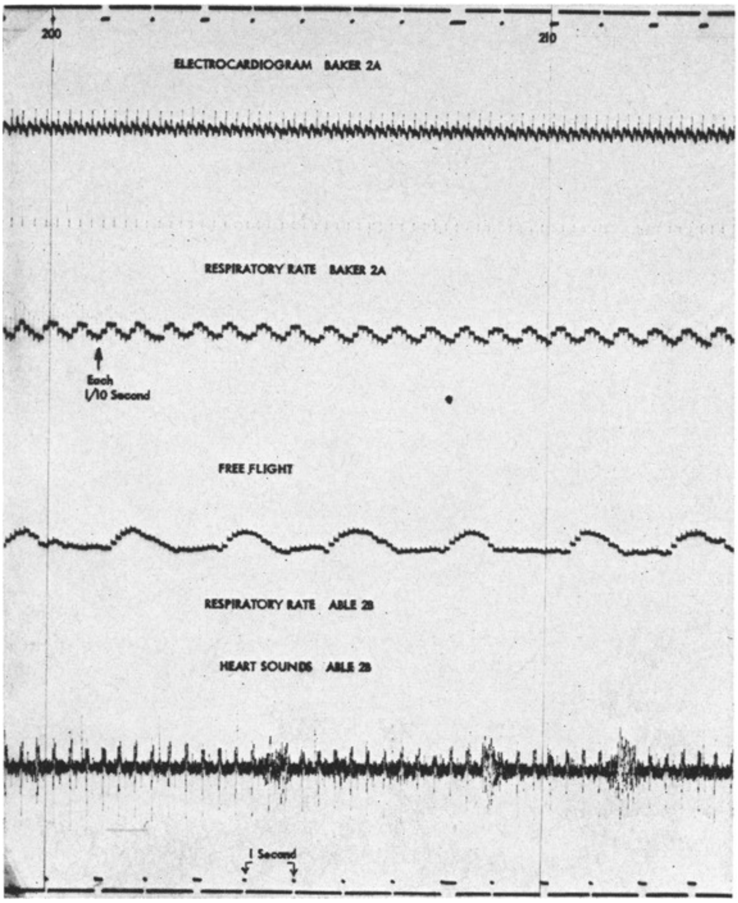

Fig. 5. Electrocardiogram and respiratory rate of a squirrel monkey ("Baker" 2A) and respiratory rate and heart sounds of the rhesus monkey ("Able" 2B) during free-flight and weightlessness.

The stress produced by the re-entry deceleration increased heart rate and respiration up to the time of impact. It was observed that Baker's respiration rate reached its peak shortly after cutoff, but heart rate maximum (about 380) occurred at re-entry. Able's cardiac rate of about 240, on the other hand, was found to be the third highest only recorded during any of the 10-second intervals, although the G-load at re-entry was about three times as high as that at liftoff. Impact again was relatively uneventful.

On the whole, recording and transmission of the biomedical data was highly satisfactory. Figure 5 shows samples of the telemetered information revealing the excellence of quality. Moreover, it should be remembered that Able and Baker were the first animals which emerged somewhat tired but unharmed from the nose cone of a ballistic missile after re-entering the earth's atmosphere from a 1500-mile journey through space.

TABLE III. CARDIODYNAMIC EFFECTS OF ACCELERATION AND WEIGHTLESSNESS

	Acceleration	Post-Acceleration Weightlessness	Weightlessness
Air Force Study	Mild tachycardia Mild hypertension Normal ECG	Decrease of tachycardia Decrease of hypertension Normal ECG	Decrease of heart rate Decrease of blood pressure Normal ECG
USSR	Mild tachycardia Mild hypertension Slight changes of ECG	Decrease of tachycardia Slow decrease of hypertension Normalization of ECG	Decrease of heart rate Decrease of blood pressure Normal ECG
von Beckh Study	Tachycardia	Fluctuating tachycardia	Decrease of heart rate
MIA	Tachycardia (Laska) Normal and decreased heart rate (Benji)	Normal heart rate (Laska) Tachycardia (Benji)	Tachycardia (Laska) Normal and decreased heart rate (Benji)
Army-Navy Study	Tachycardia Normal ECG	Tachycardia Normal ECG	Mild tachycardia Normal ECG

It is noteworthy to emphasize that the two animals survived the flight with relatively little modification of cardio-respiratory function. Comparison of the recordings of the ECG prior to launching showed that the state of weightlessness did not alter these processes and, therefore, hemodynamic phenomena appeared adequate and ensured good coronary circulation. For this to have been true, arterial blood pressure must have been maintained. Although the ECG of Able was not recorded because of a broken wire, heart sounds were of good quality and intelligible except at short periods of high outside noise.

It is rather interesting to speculate on the extreme flexibility and adaptability of the cardiovascular system. Although the episodes of high G force and weightlessness were brief, the extremes were considerable and the changes from one state to the next rapid. In spite of this the cardiovascular, hemodynamic and electric phenomena were remarkably well-maintained. Any conjecturing concerning the mechanisms for the fluctuations in cardiac and respiratory rates or the cardiac irregularities at this time would accomplish nothing. The variables were considerable and most if not all of them are quantitatively unknown. That psychological factors entered into the physiological phenomena is clearly evident from the increase in cardiac rate produced by the noise of the engine and similar missile events. Nevertheless, the entire integrated responses resulted in animal behavior sufficiently normal to ensure a safe flight.

SUMMARY

A generalized survey on the cardiodynamic effects of acceleration and weightlessness encountered in aircraft, rocket, and satellite flights is given in Table III. Tachycardia during radial and linear accelerations was observed in almost all of the human subjects and animals studied. Slight changes in the ECG were found in a few animals; but they seemed to be within the range of normal variations characteristic of their groups. There seems to be a tendency of prolonged and fluctuating tachycardia in the early state of weightlessness, and decreased cardiac activity was observed in its later states, which may be interpreted as the functional adaptation of the heart to the decreased mechanical load. No abnormal manifestations were found in the ECG. The entire series of experiments demonstrate that stresses imposed by acceleration and the episodes of weightlessness encountered in aircraft and biological missile flights are well within the range of tolerance of the human and animal organism.[5,12,17]

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