Pilot Metabolism and Respiratory Activity during Varied Flight Tasks

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METABOLISM STUDIES in aviation medicine have in the past been principally limited to observations on the effects of altitude and anoxia per se (1–3). The present study represents an effort to obtain information concerning fundamental physiologic responses to aircraft operation in terms of caloric output. It was undertaken in the belief that an overall evaluation of the pilot’s task and his energy output might well be ascertained by the measurement of metabolic rate under a variety of flight conditions.

A Link trainer and a Piper J-3 airplane were employed and the subjects for test were intentionally selected to represent varying grades of flight experience for purposes of comparison. It was well understood that the Link trainer is quite unable to reproduce physiological responses of the same degree of intensity as those resulting from actual flight, its major drawback lying in the absence of any element of personal danger. However, it was believed that its use in studies of this nature would be justified on the basis of convenience and rigid control of all experimental conditions—desirable qualities so difficult of attainment in actual flight. The extension of the study to work with the Piper airplane served as a check upon the results obtained with the Link, as well as a source of data not hitherto available.

METHODS

Pilot metabolism was obtained by means of mounting a standard clinical metabolism machine either on a wing of the Link trainer or within the cabin of an airplane. The arrangement of the apparatus is shown in figures 1 and 2. The machine employed was mechanically operated, thus eliminating the complications entailed by the use of an electrically-driven recorder.

All types of masks tested (oxygen mask, metabolism mask, modified gas mask) were found to leak during the flying of the various patterns desired, and a standard mouthpiece and nose-clip were finally adopted, an oxygen-
mask valve being inserted near the mouthpiece. This arrangement permitted the subject to shift from air to oxygen at will, and was particularly valuable when the equipment was airborne. No leakage of oxygen could be

Fig. 1. Apparatus used to determine the metabolic rate of subjects operating a Link trainer. The machine was mounted on the right wing (not shown) and connected to the subject by tubes leading directly to the cockpit. This arrangement yielded tracings in 'flight' of equal clarity to those obtained at rest.

Fig. 2. Installation of metabolism machine in a Piper J-3 airplane. The pilot was afforded an unobstructed view of the instrument panel and enabled to gauge the amount of oxygen remaining in the spirometer at all times.
detected with the apparatus thus assembled, and the tracings secured were, graphically, as perfect as those obtained under normal laboratory conditions.

A total of 103 determinations was made on the 10 subjects employed in the experiment under the following conditions:

1) Standard condition. Subject abstained from food, coffee or tobacco for 12 hours. He remained seated at the controls for 15–30 minutes prior to the standard determination.

2) Straight and level flight. The subject was required to hold the trainer straight and level for 8 minutes. Permissible error: 3 degrees of turn and 100 f.p.m. on vertical speed indicator.

3) Turns. Standard turns (3 degrees per second) were executed as follows:

<table>
<thead>
<tr>
<th>Turn Type</th>
<th>Duration</th>
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<tbody>
<tr>
<td>Straight and level</td>
<td>1 minute</td>
</tr>
<tr>
<td>360-degree turn to the right</td>
<td>2 minutes</td>
</tr>
<tr>
<td>Straight and level</td>
<td>1 minute</td>
</tr>
<tr>
<td>360 degree turn to the left</td>
<td>2 minutes</td>
</tr>
<tr>
<td>Straight and level</td>
<td>1 minute</td>
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Permissible error: Five seconds for the 360-degree turns; 2 seconds for the straight and level flights. Vertical speed within 100 f.p.m.

4) Pattern in smooth air. The pattern shown in figure 3 was devised to contain a high degree of variation in the flight task within a short time interval. Permissible error: 3 seconds for the 270-degree turn; 6 seconds for the 450-degree turn; 200 f.p.m. in vertical speed.

5) Repetition of the pattern with the ‘rough air’ turned on.

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**Airplane**

6) Take-off and flying of the standard traffic pattern; approach and landing, as shown in figure 4.

7) Rectangular pattern at an altitude of 800 feet:

- Straight and level .................................................. 2 minutes
- 180-degree turn to the left ..................................... 1 minute
- Straight and level .................................................. 2 minutes
- 180-degree turn to the left ..................................... 1 minute

Subjects of varying flight experience were used in the experiments:

- a) Four veteran military aviators (av. 3,500 hrs.)
- b) One commercial aviator (200 hrs.)
c) One private pilot (90 hrs.)
d) Two student pilots (av. 40 hrs.)
e) Two non-aviators (used in the Link trainer studies after sufficient practice enabled them to execute the patterns flown by the pilots with an equal degree of precision).

Metabolic Responses to Link Trainer Operation. In the work with the Link trainer, a total of 86 experiments was made, employing two veteran military aviators and two non-aviators. The results of these tests are shown in figure 5 in which the increased caloric output of the subjects is expressed in terms of percentage over the standard level. This standard metabolic rate was identical in both pairs (40 cal/sq.M/hr.). It will be noted that the metabolic rate was found to increase with complexity of task and that the magnitude of such increases was much greater in the non-pilots than in the veteran flyers. Note that the pilots, flying the pattern under these conditions (instrument), showed an increase in metabolic rate of 12 per cent compared to 37.5 per cent for the non-aviators.

When flying the pattern with 'rough air' both groups showed similar metabolic increases: 7.1 and 8.7 cal/sq.M/hr. for pilots and non-pilots respectively. Moreover, in terms of percentage, the pilots showed a figure of 11.2 percentage above their 'smooth air' rate for the same pattern against a comparable figure of 14.1 for the non-pilots. The additional work demanded of both pairs in negotiating the 'rough air' may therefore be said to be approximately the same.

It was concluded that pilot metabolism increases with increasing complexity of task, even when such tasks demand no appreciable increase in voluntary muscular exertion (example: turns as opposed to climbing turns), and that the increases in metabolic rates observed represent the increased amount of muscular tension (increased tendency to grip the controls and to tense the skeletal musculature, generally) entailed by the task at hand. The fact that the negotiation of 'rough air' (increased movement of the controls) produced similar percentage rises in both pilots and non-pilots was held to support this opinion. This increased muscular tension with consequent elevation of caloric output is measurably greater in, and characteristic of, the inexperienced (as compared to the experienced) pilot.

Respiration During Link Trainer Operation

Two hundred and seventy-four determinations of respiratory rate were made, employing two veteran pilots and two non-flyers (fig. 6). Both pilots and non-pilots exhibited an augmented respiratory rate with an increase in task complexity, although considerable individual variation was shown in this respiratory sensitivity. Thus, the respiratory rate was found to vary
during a single run as the pilot changed the attitude of the trainer from straight and level to turning flight.

The degree of respiratory sensitivity to an altered flight pattern was not, however, correlated with experience. On the average, nevertheless, shifts in respiratory rate were greater in the non-aviators. Thus, the most experienced pilot employed in the experiments (3800 hrs.; 200 hrs. Link trainer) proved to be the most sensitive to attitude changes, his respiratory rate altering abruptly from slow (av. 15/min.) to rapid (av. 18.5/min.) upon entering a turn. In this subject, return to level flight was uniformly characterized by a single, deep inspiration. These changes in the respiratory rate with the flight task were best exemplified during the flying of the patterns, as shown in figures 7 and 8. Note that in both pilots and non-pilots the respiratory rate was highest during the climbing turn, which in this case was made at an air speed very close to the stall. During the descending turn (a maneuver requiring an equal degree of precision, but with the possibility of a stall eliminated) the respiratory rate was once more elevated from that obtaining during level flight, but to a lesser degree in pilots and non-pilots as well.

It was concluded that pilot respiratory rate varies with the task performed even though such tasks may require insignificant changes in the manipulation of the controls. Since, moreover, a uniformly higher respiratory rate was found to be characteristic of climbing close to the stall, these respiratory responses to the flight task and attitude were attributed to increased ‘tension’ on the part of the pilot (mental concentration; gripping of the controls; generally increased muscle tension).

**Metabolism in Flight.** In these experiments the subjects were required a) to fly a standard traffic pattern (figure 4) and b) to fly a rectangular course at 800 feet altitude, the turns being standard (3 degrees per sec.) to insure uniformity of performance in so far as possible. The metabolic rates during flight were compared with the standard rate while seated in the airplane on the ground. Three pilots served as subjects (airline, commercial, student) and a total of 16 flights was made. The air was characterized as ‘rough’ during the tests. Careful timing of the phases of all flights was done by observers on the ground as a check on uniformity of performance and to determine the amount of time expended in ascent and descent in (a) above, since this was quite necessary for accurate calculations of changes in barometric pressure, and consequently in gas volume corrections.

The results of the tests in which a traffic pattern was flown are reproduced in figure 9. As in the Link trainer studies, caloric output was found to be definitely correlated with experience. The standard metabolic rate averaged
49.9 cal/sq.M/hr. in the subjects used, varying from 48.4 to 52.6. The airline, commercial and student pilots' average caloric output while flying the pattern was 81.5, 87.4 and 91.4 cal/sq.M/hr., respectively. It was concluded that this correlation in caloric output and flight experience could best be explained on a basis of muscular tension in flight. The same correlation was indicated by experiments in which a rectangular pattern was

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**Fig. 7.** Effects of pattern flying on the respiratory rate of pilots operating a Link trainer.

**Fig. 8.** Effects of pattern flying on the respiratory rate of non-pilots operating a Link trainer.

**Fig. 9.** Metabolic rates of airline, commercial and student pilots flying a traffic pattern in an airplane. The 'standard' rate was that obtained while the subject was seated, at rest, at the controls.

**Fig. 10.** Effects of pattern flying on the respiratory rate of airplane pilots.
flown at 800 feet. Here the caloric output of the student pilot increased by 70.2 per cent, while that of the airline pilot rose but 12.1 per cent.

Respiratory Rate in Flight. Changes in respiratory rate during various phases of the flight task were determined by correlating the timed tracing obtained from the metabolism machine within the airplane with time records made by observers on the ground. Figure 10 shows an average of these determinations. It was found that, as in the case of the Link trainer study, the respiratory activity of the pilots was altered by the demands of the specific flight task momentarily involved; further, that the respiratory rate was lowest on the ground before take-off and rose during take-off and the turns at the upwind limit of the pattern. During straight and level flight respiratory activity declined, but subsequently rose to its highest value during the approach and landing—a period during which demands on pilot concentration and skill are greatest.

It was concluded that respiratory activity during flight (as in Link trainer operation) varies with task complexity and is greatest during those maneuvers demanding maximum concentration, skill and judgment on the part of the pilot.

DISCUSSION

A review of available (unclassified) literature has failed to reveal studies comparable to the above, the majority of related observations being confined to high altitude effects (1–3) rather than applying directly to aircraft operation. Through fortuitous circumstance, a memorandum report (AAF) by Penrod (4) was obtained in which he has described a study of respiratory requirements for Link trainer flying. He found that 'rough air' increased the ventilation 'moderately'. However, in this work, pressure drop in oxygen cylinders (connected to the mask through a demand valve) was the criterion employed, and such a method cannot yield quantitative data on oxygen consumption, caloric output or the rate and depth of the respirations.

Pilot metabolism was selected for study since it constitutes a single determination, conveniently made in aircraft, which yields quantitative data on work output, oxygen requirement, muscular tension, comparative activity with varying flight tasks and the comparative difficulty of the various maneuvers executed as well as graphic records of respiratory responses to variations in task in pilots differing in experience, temperament, etc.

The Link trainer was selected as the instrument of choice (in contradistinction to the airplane) for the reason that its use permits the rigidity of control essential to obtaining valid and comparable data. Strict standards of performance may be adopted with this equipment, and all variations in indicated air speed, vertical speed, rate of turn, the time of all phases of
the ‘flight’, altitude, etc., may be readily observed while an accurate graphic record of each performance is secured by means of the automatic recorder or ‘crab’. In an airplane in flight such strict comparisons cannot be made due to variations in the turbulence of the air and because it is impossible for the subject to duplicate exactly his successive performances. Thus, in such a simple problem as taking off and landing it is well recognized that “no two landings are alike”. The best that can be done is to perform each test under as nearly identical conditions as possible with strict adherence to those procedures which are subject to control. In spite of these shortcomings of the airplane as a laboratory instrument, however, it is necessary that results obtained through other means such as the Link trainer be validated in the air, since it is the task of flying the airplane with which we are ultimately concerned, and the physiological stresses of flight can be adequately investigated only in studies involving the actual operation of aircraft.

That caloric output as well as respiratory rate and depth may be strongly influenced by psychic factors was apparent from the inception of the work. Thus, the most experienced pilot employed in the Link studies showed the most striking susceptibility to the execution of turns as evidenced by the abrupt onset of rapid and shallow respirations as the turn was entered, and one or two very deep inspirations at the conclusion of the maneuver. This respiratory pattern was invariably present. A commercial pilot expressed concern over the use of a short runway necessitated by wind conditions. Metabolic tracings secured from this man showed a notable increase in oxygen consumption and respiratory rate from the beginning of the approach to the field until ground contact was made. Again, a private pilot employed on a single occasion exhibited such an abnormally rapid respiratory rate (32/min.) when aloft that the data secured from the tests were discarded since it was considered he could not accustom himself to the use of the metabolism machine while in flight. Experienced flight instructors expressed the opinion that this subject was one who “would not make a military aviator” due to apprehension while flying.

While the experiments described are elementary in nature and limited in number and scope, it appears quite possible that such studies may have rather far-reaching implications in such fields as pilot selection, aeroneurosis and flying fatigue. At present, adaptability to the task of flying as well as the degree of tension under which the pilot may labor are estimated by clinical examination, aptitude tests and other means of a subjective nature. If it should be found that quantitative measurements of caloric output are, indeed, reliable criteria for gauging the stresses and strains of flight, further experiments of this nature should prove well worth while.
SUMMARY

1. Pilot metabolism was found to increase with increasing complexity of flight task, and such increases were measurably greater in the inexperienced as compared with the experienced pilot.

2. The respiratory rate of pilots was found to vary with the task performed. These variations were in the same direction in inexperienced and experienced subjects.

3. The observed increases in metabolism and respiratory rate were not invariably correlated with the amount of muscular activity essential to the execution of the maneuvers executed, and were attributed to generalized increases in skeletal muscle tension.

4. The phenomena summarized above were observed both in Link trainer operation and in flying an airplane.

5. The implications of these observations in aviation medicine, generally, are discussed.

REFERENCES


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