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16. Abstract

Forty male subjects participated in a study to examine the relationship between low-grade hypoxia and vigilance performance. At an altitude equivalent of 11,500 feet in a low-pressure chamber, subjects without supplemental oxygen did not respond differently from well-oxygenated subjects at the same altitude with respect to such physiologic measures as heart rate, respiratory frequency, internal body temperature, or plasma concentrations of glucose or lactate. Nor were these measures significantly different between groups studied at altitude and ground level controls. The only evidence of hypoxia observed in the altitude/room air group was in terms of a decrease in blood oxygen saturation measured with an earpiece oximeter. Vigilance performance deteriorated with time in all groups. No significant differences, however, could be detected between the hypoxic group and the well-oxygenated groups. It is concluded that a four-hour exposure to 11,500 feet of altitude has no demonstrable effect on the performance of a simple vigilance task under the conditions examined here. Because of the limitations concerning test subjects and the test used in this study, its results do not affect compliance with FAR 91.32, supplemental oxygen rule.

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EFFECTS OF LOW-GRADE HYPOXIA ON PERFORMANCE IN A VIGILANCE SITUATION

I. Introduction.

Many studies evaluating various aspects of psychophysiological performance have indicated that effects of hypoxia are not usually observed below altitude equivalents of 12,000 feet[5]. Despite such a generality, however, it is recognized that some tests of psychomotor performance seem more sensitive to the effects of low-grade hypoxia than do others.[7 11] As examples, Rahn and Otis[14] found that hand steadiness was significantly affected at 12,000 feet, and more recently Denison *et al.*[3] demonstrated that learning a new orientation task was affected at as low an altitude as 5,000–8,000 feet. In the latter study the subjects were exercised to a level of energy expenditure comparable to that of a pilot in active flight.

In view of the considerable amount of work done on the effects of hypoxia on other types of performance, it is surprising that the area of vigilance has been ignored. Recent treatments of the problems of vigilance have covered the effects of such environmental factors as heat and cold[1 2], but data on the effects of altitude are conspicuously lacking.[6 10] It was the intent of this study to examine whether simple vigilance performance could be affected by low-grade hypoxia. For the purposes of this paper, low-grade hypoxia is defined as the degree of hypoxia generated by altitude exposure up to 12,000 feet. This altitude has been considered to be the maximum flight altitude that can be safely maintained in unpressurized general aviation aircraft without supplemental oxygen.[4] Studies examining the relationship between hypoxia and vigilance may have a direct application to the monitoring functions required of the general aviation pilot (aircraft watch, instrument scanning, etc.).

II. Methods.

A. *Subjects.* The subjects used in this study were 40 male volunteers between the ages of 19 and 30 years. Most of the subjects had no prior experience with chamber depressurization. After arriving at the laboratory in a post-absorptive state (12 hours), each subject was medically examined for his fitness to participate in a depressurization experiment, even though half the tests conducted were at ground level conditions. No attempt was made to differentiate smokers from non-smokers. Smoking is the most commonly encountered condition associated with a lowering of altitude tolerance. Because subjects were assigned to the four groups at random, it was assumed that the distribution of smokers in each of the groups was uniform.

Approximately 90 minutes before the test, each subject was given a standard meal consisting of a commercial preparation of "instant breakfast." About one hour before the test run, each subject read a standard set of test instructions and was permitted to practice the vigilance task for a 30-minute period. Subjects were paid for their participation.

B. *Vigilance Testing.* The vigilance situation was created by requiring the subject to monitor a simple light display. Two small blue lights were mounted 30 cm apart on a panel. The panel was placed approximately 65 cm in front of the seated subject at eye level (Fig. 1). Illumination of the panel lights was automatically controlled by a relay device (Fig. 2) located outside the altitude chamber. The control unit permitted the panel lights to be energized alternately at the rate of one flash per second. The duration of the flash was approximately 75 milliseconds. At any time in the cycle, an interrupter switch could be activated which would prevent the next regular flash from occurring. The failure of a flash to occur when it should have constituted the signal to be detected by the subject.

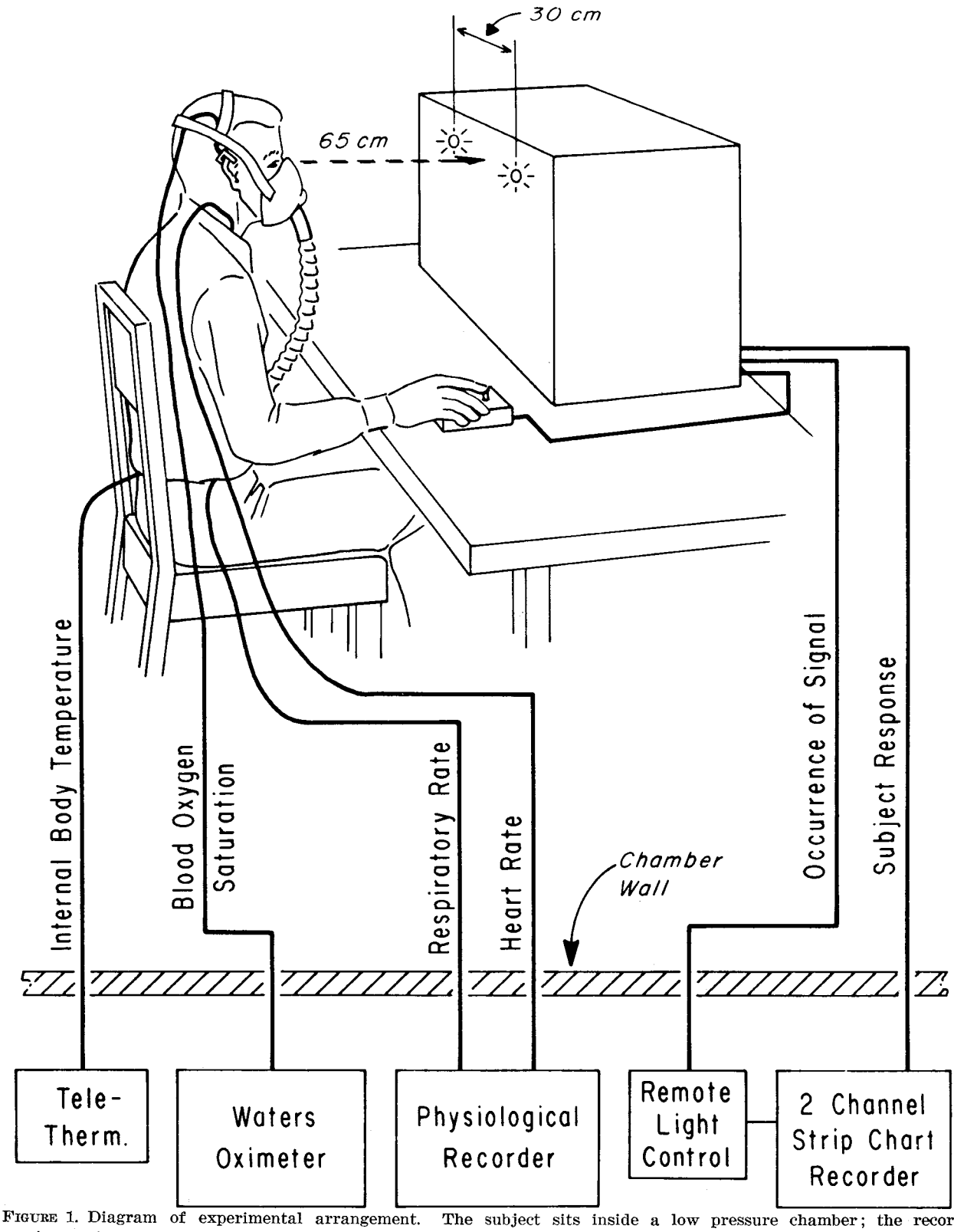

FIGURE 1. Diagram of experimental arrangement. The subject sits inside a low pressure chamber; the recording equipment is monitored from outside the chamber. Heavy lines represent the electrical leads between the sensors and the recording equipment. The subject's only activity is to acknowledge the occurrence of a signal by depressing the button before him.

The vigilance test was administered in four consecutive one-hour sessions with a ten-minute rest period between each session. Four different and random schedules were prepared for signal presentation through time, one schedule for each hourly session. The schedules were based on giving one signal within each five-minute interval for the hour (12 signals for each one-hour session). The inter-signal intervals were irregular and varied between 20 and 564 seconds.

When the subject detected a signal he acknowledged it by depressing a button before him. Both the occurrence of the signal and the response to it were recorded on a moving strip chart. If a signal was not acknowledged within ten seconds after its presentation it was scored as "undetected" or "missed." Responses when no signal was presented were also scored as errors ("additions"). Performance on the test was scored according to the number of signals during each session that were not detected, and the number of responses that were made without an appropriate signal.

C. *Physiological Measures.* Because the vigilance situation characteristically involves a minimum of muscular activity, it occurred to us that measures of internal body temperature and heart rate might be useful in reflecting the gen-

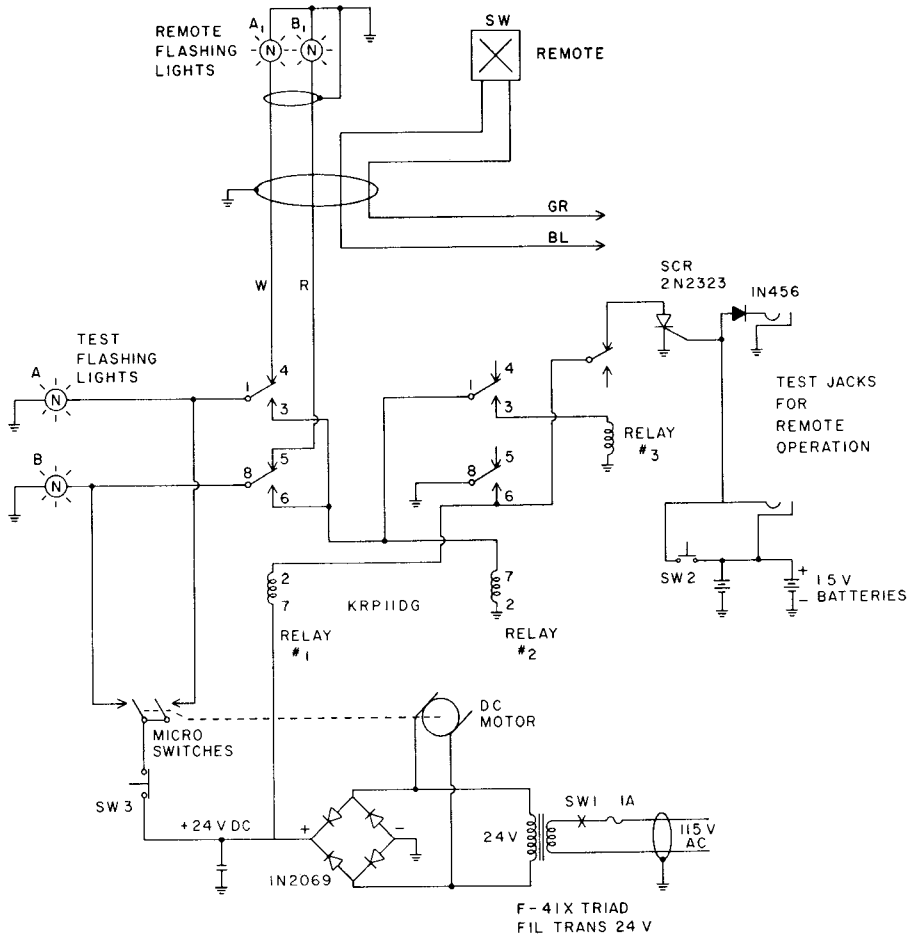

FIGURE 2. Schematic diagram of flashing light circuit. Power switch SW–1 permits DC motor to run and operate microswitches alternately. DC voltage applied alternately to test lamps A and B and to remote lamps A_1 and B_1. Relays #1, #2 and #3 are not contacting. Contacting switch SW–2 applies 1.5 volts on the gate of SCR 2N 2323. When conducting, the SCR provides a ground for relay #1. Activating relay #1 removes voltage from remote lamps and applies voltage to relay #2. Activating relay #2 provides a holding for relay #1 and also provides voltage to relay #3. Activating relay #3 opens the circuit to SCR. On the next cycle the microswitch opens to remove voltage from relay #2. Deactivating relay #2 removes holding circuit for relay #1 and contacts are returned to original position and the lamp not deactivated will glow again. Thus contacting SW–2 interrupts the flash sequence causing one lamp to skip a flash. Contacting SW–3 removes voltage from both lamps so that neither flashes.

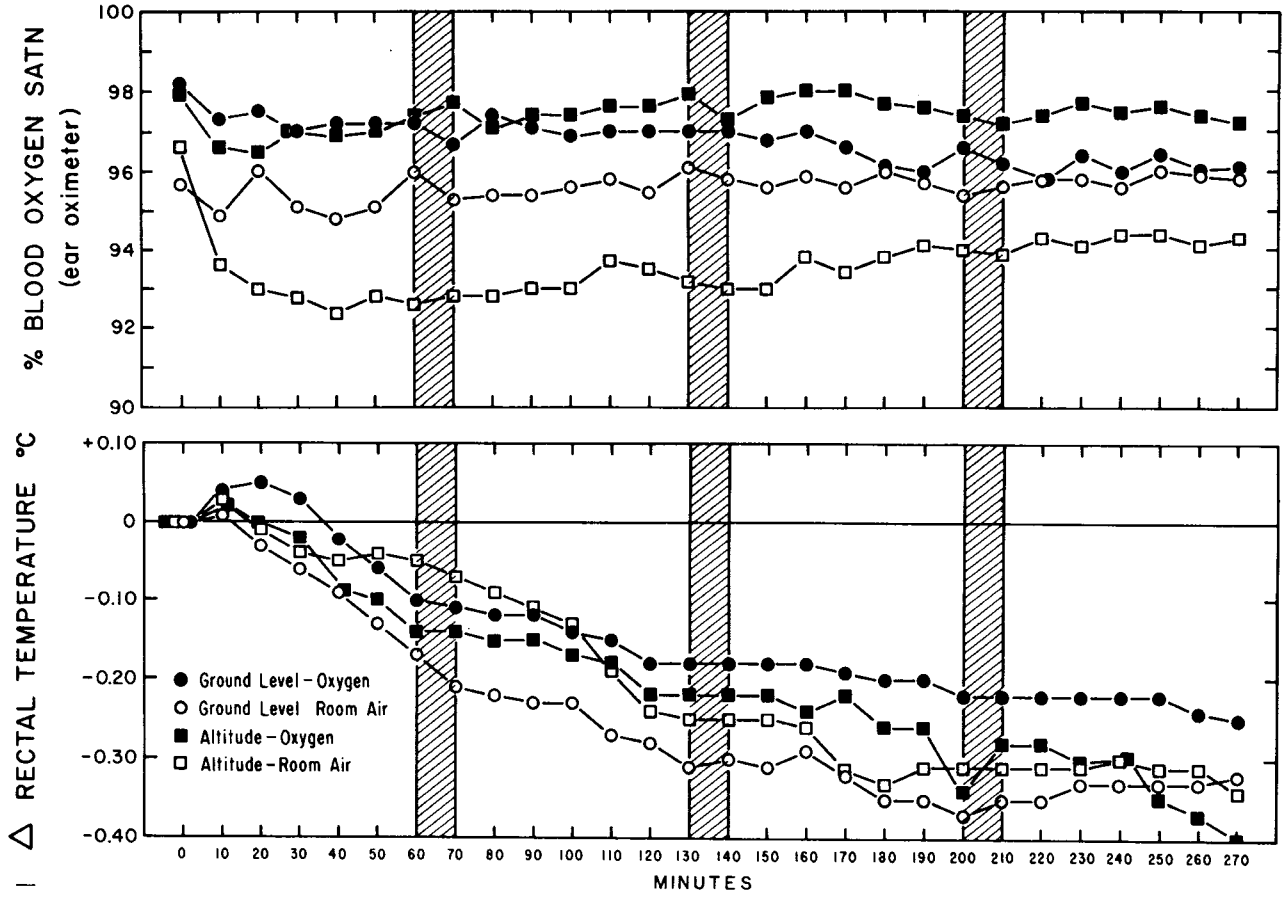

FIGURE 3. Blood oxygen saturation (upper panel) and change in rectal temperature (lower panel) during four consecutive hours of vigilance testing. The shaded areas represent the ten-minute rest periods permitted between one-hour testing sessions. Each point represents the mean value (or change) of ten subjects. The mean value for the temperature measure made at the beginning of the test was represented by zero.

eral level of "arousal" during the test. Heart rate was counted from recordings of the electrical activity of the heart (non-standard EKG) and internal body temperature was monitored with a calibrated thermistor probe inserted 10 cm into the rectum and was read on a YSI Telethermometer. Measures associated with the condition of hypoxia were respiratory rate, plasma glucose and plasma lactate concentrations and blood oxygen saturation. Respiratory rate was counted from recordings of thoracic displacement sensed with a mercury-in-rubber strain gauge. Plasma glucose was measured by an Auto-Analyzer technique adapted from the fluorometric method of Guilbault.[8] Plasma lactate was measured according to the method of Schön.[15] Blood oxygen saturation was monitored at ten-minute intervals using a Waters earpiece oximeter. Because of the recognized limitations in the measurement of arterial blood oxygen saturation by indirect oximetry, percentage saturation data given in this report should be considered in terms of a relative change rather than in terms of an absolute estimate of arterial oxygen saturation. The oximetry values in this report are consistent with other published values for oxygen saturation obtained by ear oximetry.[9 12 13]

D. *Procedure.* Test subjects were randomly divided into four groups of ten men each. All of the tests were conducted in a low-pressure chamber that was temperature controlled at 75° F. Two of the subject groups were studied at 725 mm Hg, which is the equivalent of 1,284 feet and is ground level in Oklahoma City. The other two groups were tested at 493 mm Hg, the pressure equivalent of 11,500 feet. Both ground level and altitude groups were examined with and without supplemental oxygen. Those subjects not breathing oxygen breathed room (ambient) air. Each subject was provided with a

standard demand-type oxygen mask that was worn at all times except during part of each ten-minute rest period. The subject was permitted to remove his mask at these times for purposes of general comfort. The mask was off the subject for approximately the first five minutes of the rest period.

Neither the test altitude nor the composition of the breathing mixture was revealed to the subjects. When an altitude condition was under study, chamber depressurization to the test pressure (493 mm Hg) occurred over a five-minute period. Subjects studied under ground level conditions (725 mm Hg) were made to experience an ascent to 3,000 feet and a slow return to ground level to simulate chamber operation. This procedure also required five minutes. Only one subject was studied at a time.

Venous blood samples (5 ml) were taken from the subjects just before the start of the test, during each of the three rest periods, and immediately following the last vigilance session. The blood was chilled and centrifuged and the plasma analyzed as previously indicated.

III. Results.

The exposure of subjects to an altitude equivalent of 11,500 feet for four hours without supplemental oxygen resulted in a decrease in blood oxygen saturation to approximately 93–94% from initial levels near 97% (Fig. 3, upper panel). By contrast, subjects breathing 100% oxygen, whether at ground level or at altitude, maintained blood oxygen saturation between 96 and 98% over the four-hour test. Subjects breathing room air at ground level showed blood oxygen saturations near 96% over the entire period. According to these data, the degree of hypoxia experienced by the altitude/room air group may be considered as no more than mild.

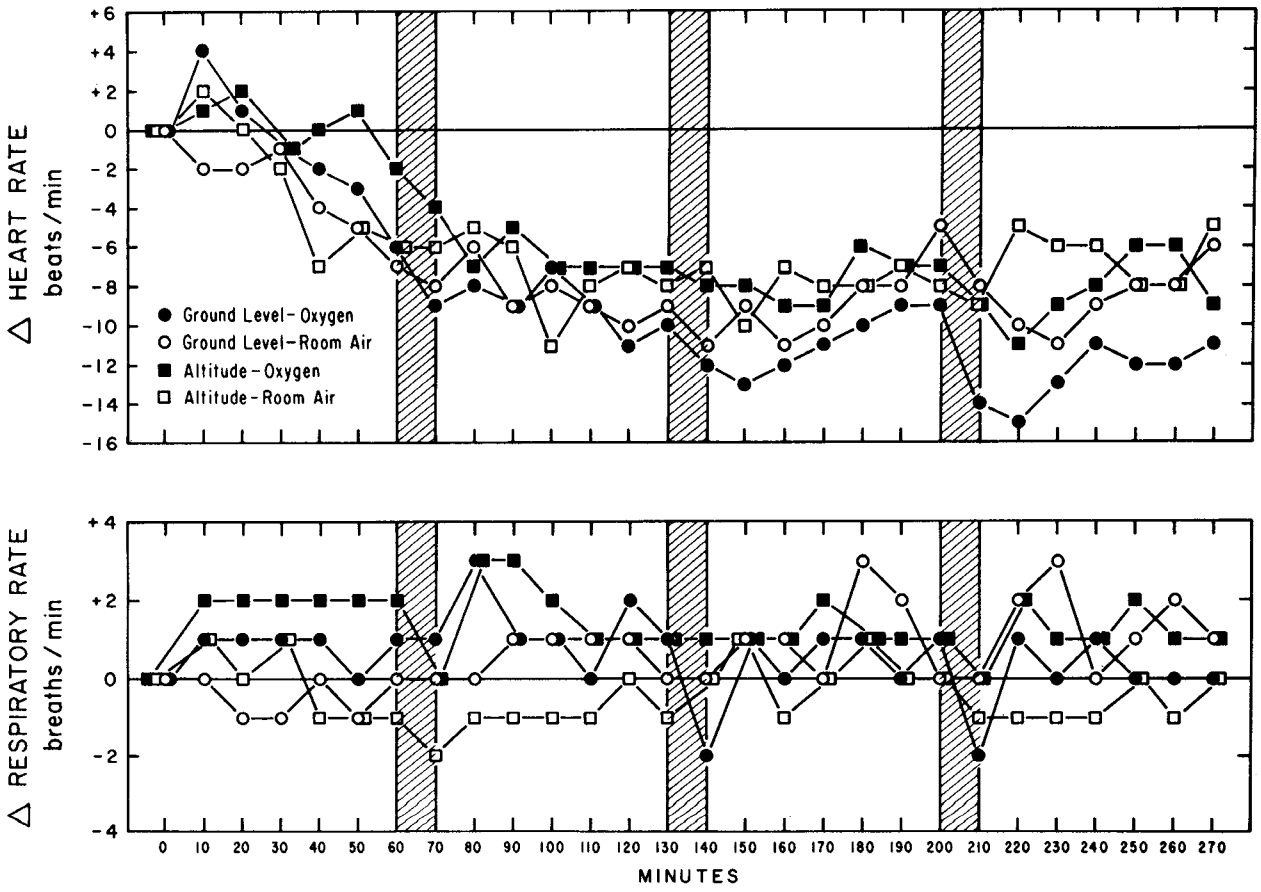

FIGURE 4. Changes in heart rate (upper panel) and in respiratory rate (lower panel) during the four-hour vigilance test. Shaded areas represent ten-minute rest periods; each point is the mean change of ten subjects. Mean values for the measures made at the start of the test were represented by zero.

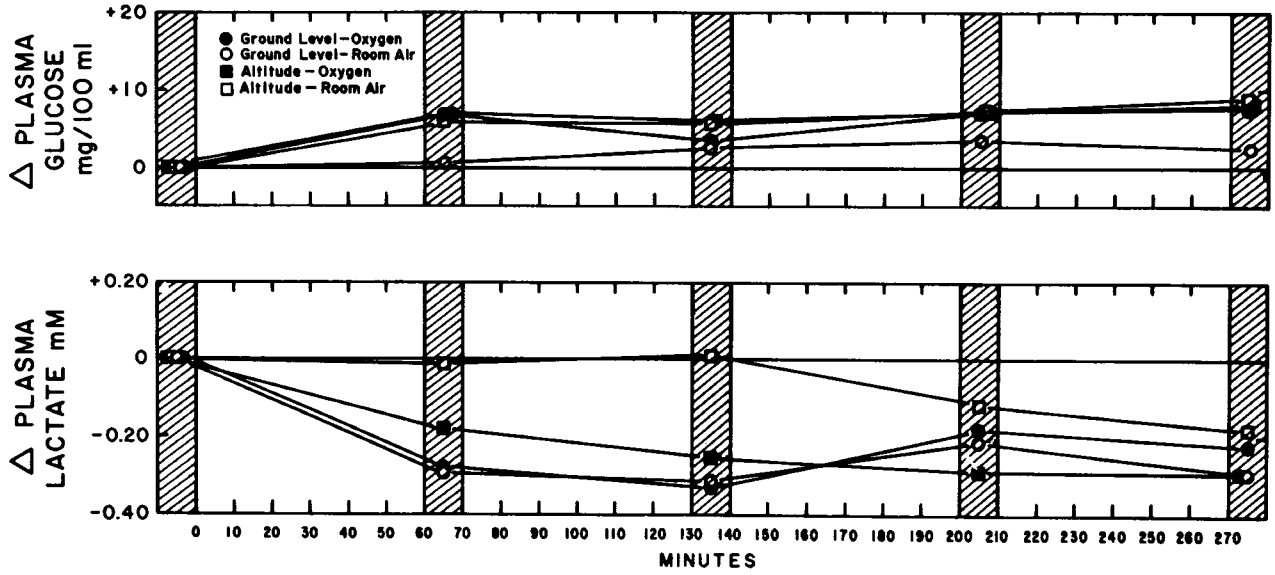

FIGURE 5. Changes in the plasma concentrations of glucose (upper panel) and lactate (lower panel) during four hours of vigilance testing. Shaded areas represent the rest periods between test sessions. Blood samples were taken at the beginning of the test (zero values) and during each of the rest periods. Each point represents the mean change of ten subjects.

The changes in internal body temperature during the vigilance test are shown in the lower panel of Figure 3. During the first two hours of the test, internal body temperature declined steadily in all groups. During the last two hours of the test, internal body temperature stabilized at levels 0.2–0.4° C below initial temperatures with no marked difference appearing in any particular group.

Heart rate changes are shown in Figure 4 (upper panel). In general, the heart rate data are similar to the changes in internal body temperature, declining during the first half of the test and stabilizing at some lower level during the latter half of the test. Despite the fact that heart rate changes were variable from group to group, the general tendencies of this measure were clear. No condition effect was observed.

Respiratory rate changes (Fig. 4, lower panel) were also variable among groups and fluctuated ±3 breaths per minute from the initial group measure. No clear difference was detected in this measure as a function of altitude or breathing mixture condition.

The plasma measures of glucose and lactate are presented in Figure 5. The general trend in plasma glucose was to increase slightly during the first hour of the task. Thereafter plasma glucose levels remained elevated at about 8–10 mg/100 ml above the initial levels measured. The increase detected in the group breathing room air at ground level was somewhat less than that observed for the other three groups. In each of the three well-oxygenated groups plasma lactate levels decreased during the first hour by 0.2–0.3 mM and remained at approximately this level for the remainder of the four-hour session. In the group breathing room air at altitude the plasma lactate levels were unchanged from initial levels during the first and second hour of the test. The first noticeable decrease in plasma lactate levels in this group occurred after three hours, and by the end of the four-hour session lactate levels were similar to those of the other three groups.

Performance data were examined in several ways to evaluate condition effects. In the first comparison the errors made by each subject during the first 30 minutes of each hour testing session were compared to his errors made during the last 30 minutes of each session. Misses and additions were considered independently. The number of individuals making more errors in the last half of each hourly session was evaluated in a Chi Square contingency table. No significant differences in additions were found between conditions, nor was an overall effect detected. With respect to missed signals examined in the

same way, condition effects were also unable to be detected, but a significant overall effect was found ($P<0.05$). This suggests that, considering all subjects, vigilance performance decreased progressively during the course of each hourly session with this specific task.

The second analysis considered the number of individuals making more errors during the last two hours of the test as compared to the first two hours. Similarly, the Chi Square contingency table revealed no significant condition or overall effects with respect to additions. A significant overall effect was detected in missed signals ($P<0.01$), but again no significant condition effect was observed. In general then, with all subjects considered, vigilance performance also decreased progressively over the entire four-hour test (Fig. 6). The observation that *all* of the hypoxic subjects responded with more misses in the latter half of the test suggests that there may be a subtle effect on the performance of those subjects (Table 1). The effect, however, was not great enough to be detected statistically in this small sample because of the high variability in subject responses.

A third analysis, the Kruskall-Wallis analysis of variance, was made to examine possible condition effects through the use of rank data. No statistically significant differences were found among conditions with respect to either additions or misses.

IV. Discussion.

Considering first the physiological data, it appears that exposure of subjects to an altitude equivalent of 11,500 feet without supplemental oxygen resulted in a level of hypoxia too subtle to be reflected in heart rate and respiratory rate measurements. In both of those measures the changes experienced by hypoxic subjects were not distinctly different from the changes shown

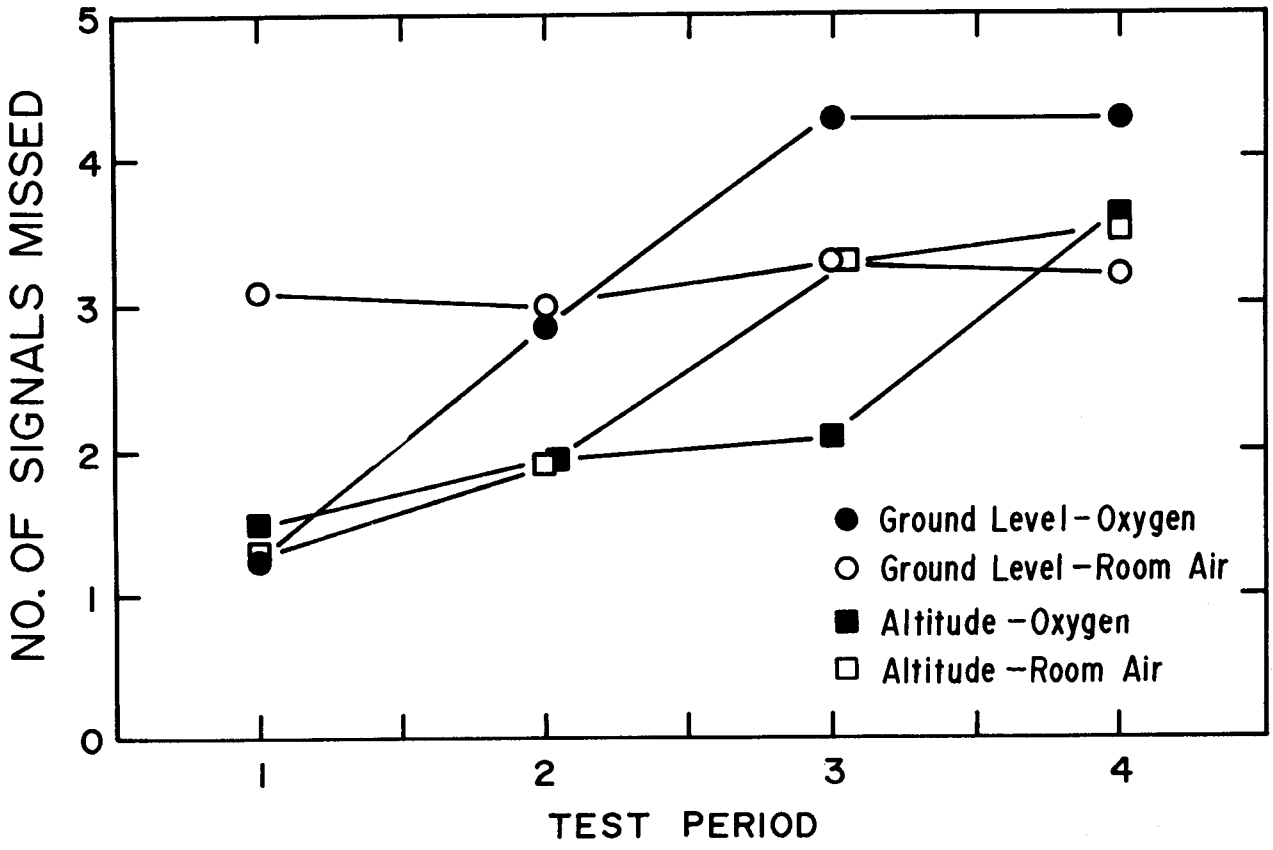

FIGURE 6. Vigilance performance by period of testing. Test periods 1–4 represent the first through the fourth consecutive testing sessions. Each point is the mean value of ten subjects. A positive slope indicates poorer performance (number of signals missed) as the test progresses.

TABLE I.—Relative vigilance performance during the four hour test period

Condition	Number of Subjects Scoring More Misses in the Second Half of the Test Relative to the Total Number of Subjects Tested
Ground level; O_2	7/10
Ground level; Room Air	6/10
Altitude; O_2	7/10
Altitude; Room Air	10/10

by well-oxygenated subjects. The evidence that subjects at altitude without supplemental oxygen were mildly hypoxic rests principally on the oxygen saturation data. It is realized that both the level of hypoxia (oxygen saturation) and the response to hypoxia of the heart and respiratory rates are closely related to the oxygen requirements of the subjects at altitude. Since the task studied here was (by design) a sedentary one, demanding a minimum of muscular activity, it is apparent that "adequate" tissue oxygenation was provided with little, if any, cardiopulmonary adjustment. The sedentary nature of the task is emphasized by the gradual decrease in both internal body temperature and heart rate to stabilized levels below initial values. The absence of a condition effect in those data further suggest that the level of "arousal," as might be evident through increased muscular activity or muscular tension, was not different in hypoxic subjects as compared with oxygenated subjects.

Changes in the plasma glucose levels among subjects in the different conditions were approximately the same. All groups showed a slight increase from the starting levels within the first two hours of the test with no further change beyond that time. This increase in the plasma glucose levels is believed to be a postprandial response resulting from the standard meal given 1.5 hours before the beginning of the test. These data provide no evidence that the plasma glucose level responds to an altitude exposure of 11,500 feet.

Since the plasma lactate represents the net result of lactate production (muscular activity) and lactate utilization (liver uptake, pyruvate oxidation) the general decrease observed in the well-oxygenated subjects may reflect more a muscular relaxation effect rather than increased utilization. In these terms it would appear that the altitude subjects without supplemental oxygen took longer to relax or adjust to the task. Another possibility, though without the appropriate data it remains only a speculation, depends on a decrease in pyruvate oxidation under oxygen limiting conditions. If the subjects at altitude without extra oxygen also experienced a decrease in lactate production (muscular relaxation), but at the same time incurred decreased pyruvate oxidation, the lowering of the plasma lactate might not be as marked as that observed in normoxic subjects. Consistent with this suggestion, there is a slight increase in the oxygen saturation of the hypoxic group after two hours on the test (from ~ 93% to ~ 94%; Fig. 1). It is at about this time in the test that plasma lactate begins to decrease in this group.

From a performance standpoint, the level of hypoxia incurred by an altitude exposure of 11,500 feet seems to be of little consequence when vigilance is the primary consideration. It should be realized that the "test" of vigilance used in this study represents only a single instance of an extremely wide spectrum of possible "vigilance situations." While mild hypoxia may have little additional effect in the simplest instances of vigilance performance, it is conceivable that more sophisticated vigilance situations might be susceptible to performance decrements under similar conditions of oxygen deficit. This again brings up the question of varying sensitivities of performance tests to hypoxia. Although the group data would suggest the conclusion of no hypoxia effect, viewing the data based on individual responses might suggest that the test used in these experiments was just at or near the threshold of sensitivity for the degree of hypoxia achieved. The results of the present study indicate that the FAA oxygen rule (FAR 91.32, Supplemental Oxygen) is well-conceived and that, insofar as vigilance is concerned, no ill-effects need be anticipated, at least to 11,500 feet. Because the study concerned itself with only young males, however, it may not be possible to extrapolate the significance of these findings to the general aviation community. Further, the fact that the study did not evaluate the influence of age, obesity, smoking, fatigue, etc., may limit the conclusiveness of our interpretations since these factors tend to decrease altitude tolerance.

If it is necessary to examine the problem further, it seems clear that several tests of vigilance should be studied at several altitudes above 12,000 feet in order to establish critical altitudes and whether each of the situations is equally sensitive to hypoxia (amount of performance decrement per unit increase in altitude, or per unit decrement in blood oxygen saturation).

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