BLOOD OXYGEN SATURATIONS AND DURATION OF CONSCIOUSNESS IN ANOXIA AT HIGH ALTITUDES

CARL E. HOFFMAN, ROBERT T. CLARK, JR. AND E. B. BROWN, JR. 1

From the School of Aviation Medicine, Naval Air Station, Pensacola, Florida

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Survival times at high altitudes following failure of oxygen equipment in military aircraft has been a critical problem. With the advent of pressurized cabins for stratospheric flying in both military and commercial aviation, the problem of survival in the event of mechanical failure resulting in loss of cabin pressure becomes an important consideration. Two investigators, Mackenzie (1) and Hemingway (2), have reported on the duration of consciousness of human subjects breathing air at high altitudes. Only one, Hemingway (2), determined blood oxygen saturations during the experiments. In each instance the studies were made with a number of individuals in the low pressure chamber. Both investigators used the ability to write as a measure of useful consciousness. It is the opinion of the authors of this paper that the duration of consciousness which could be considered useful is shorter than that measured by handwriting ability.

The purpose of this investigation is to present the following information on the reactions of man to breathing air at altitudes ranging from 28,000 to 38,000 feet: a, period of useful consciousness; b, times to tremor and imminent unconsciousness; c, blood oxygen saturations at termination of useful consciousness, at tremor, and at imminent unconsciousness.

METHODS. Subjects consisted of flight students and Hospital Corpsmen ranging in age from 18 to 30 years. The 6 Hospital Corpsmen were used as subjects at each of the 4 altitudes, but each flight student acted as subject only once.

Blood oxygen saturations were estimated with a Millikan oximeter by conventional oximeter technique. Pressure altitudes were determined by a mercury manometer, and oxygen pressures in the chamber were recorded from a continuous oxygen analyzer. The accuracy of the oxygen analyzer was checked periodically against the Haldane-Henderson gas analyzer.

At sea level the oximeter was standardized and the subject was fitted with an oximeter ear piece. Initial blood oxygen saturation, with the subject breathing air at sea level, was set at 98 per cent. Using diluter-demand oxygen equipment the subjects were taken one at a time to a simulated altitude in the low pressure chamber. To insure that the subject was receiving 100 per cent oxygen prior to mask removal, the oxygen regulator was set to the "100 per cent oxygen" position at 27,000 feet during ascent on each run. Maximum ventilation was maintained in the chambers while at altitude, and, by means of a suction pump, samples of the chamber air were constantly drawn from just above the subject's head.

1 This problem was suggested and the preliminary phases of the investigation were supervised by Lt. C. S. White (MC) USN.
through the oxygen analyzer. After approximately 5 minutes at altitude, the
instruments were read, and the subject had his mask removed and breathed am-
bient air. He was given the task of naming and sorting cards from an ordinary
pack, placing cards in one of four slots in a box according to card suit.

Two observers accompanied the subject on each run. It was the task of one
observer to remove the mask and to report the subject's reactions, while the other
recorded data and read the instruments. Both observers were placed in the
chamber so that their exhaled oxygen was always carried away from the subject.
Times to error, onset of convulsive-like movements, and mask replacement

TABLE 1
The mean and the range of times to error, tremor and mask replacement on 26 subjects

<table>
<thead>
<tr>
<th>ALTITUDE</th>
<th>Time in seconds</th>
<th>Error</th>
<th>Mean</th>
<th>Range</th>
<th>Tremor</th>
<th>Mean</th>
<th>Range</th>
<th>Mask replacement</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>feet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>28,000</td>
<td></td>
<td>110 ± 5.5</td>
<td>50-178</td>
<td>106 ± 4.2</td>
<td>70-160</td>
<td>141 ± 5.3</td>
<td>100-210</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30,000</td>
<td></td>
<td>73 ± 3.1</td>
<td>40-100</td>
<td>71 ± 2.2</td>
<td>45-100</td>
<td>98 ± 2.2</td>
<td>80-115</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35,000</td>
<td></td>
<td>46 ± 2.2</td>
<td>25-68</td>
<td>51 ± 1.6</td>
<td>40-70</td>
<td>72 ± 1.6</td>
<td>60-90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38,000</td>
<td></td>
<td>35 ± 1.3</td>
<td>20-45</td>
<td>35 ± 1.3</td>
<td>25-45</td>
<td>47 ± 1.4</td>
<td>35-60</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

TABLE 2
The mean and the range of blood oxygen saturations at the time of error, tremor and mask replacement on 26 subjects

<table>
<thead>
<tr>
<th>ALTITUDE</th>
<th>Saturation in per cent</th>
<th>Error</th>
<th>Mean</th>
<th>Range</th>
<th>Tremor</th>
<th>Mean</th>
<th>Range</th>
<th>Mask replacement</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>feet</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>28,000</td>
<td></td>
<td>61 ± 1.77</td>
<td>45-76</td>
<td>62 ± 1.71</td>
<td>45-78</td>
<td>54 ± 1.85</td>
<td>40-73</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30,000</td>
<td></td>
<td>63 ± 1.6</td>
<td>45-78</td>
<td>63 ± 1.8</td>
<td>45-82</td>
<td>54 ± 1.6</td>
<td>40-68</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35,000</td>
<td></td>
<td>70 ± 1.6</td>
<td>50-84</td>
<td>66 ± 1.7</td>
<td>48-82</td>
<td>58 ± 1.0</td>
<td>40-72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38,000</td>
<td></td>
<td>63 ± 1.6</td>
<td>45-82</td>
<td>64 ± 1.9</td>
<td>45-80</td>
<td>57 ± 1.4</td>
<td>40-66</td>
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</table>

were noted and recorded. Readings of the oximeter and oxygen analyzer were
recorded at 10 second intervals. The mask was replaced after the subject had
lost physical and mental co-ordination, and unconsciousness was imminent.
Readings were continued until the blood oxygen saturation had returned to
approximately its original value after which descent was begun.

RESULTS. Table 1 presents the mean and the range of times to error, tremor,
and mask replacement on 26 subjects at each of the 4 altitudes studied.

Table 2 gives the average blood oxygen saturations at the appearance of error,
tremor, and imminent unconsciousness. In figures 1 to 4 the fall in blood oxygen
saturations, following the change from 100 per cent oxygen to air, is graphically
illustrated for each of the 4 altitudes. These figures show mean and individual
Fig. 1. Mean and individual blood oxygen saturation at 20 second intervals following mask removal at 28,000 feet. Saturations are included for each individual until the time the mask was replaced. Initial blood oxygen saturations were 100 per cent in all cases.

Fig. 2. Mean and individual blood oxygen saturations at 10 second intervals following mask removal at 30,000 feet. Saturations are included for each individual until the mask was replaced.
Fig. 3. Mean and individual blood oxygen saturations at 10 second intervals following mask removal at 35,000 feet. Saturations are included for each individual until the mask was replaced.

Fig. 4. Mean and individual blood oxygen saturations at 10 second intervals following mask removal at 38,000 feet. Saturations are included for each individual until the mask was replaced.
saturations at 10 second intervals for altitudes 30,000, 35,000 and 38,000 feet; for 28,000 feet they are presented for every 20 seconds. Comparison of the average rates of fall of blood oxygen saturations at the 4 altitudes is shown in figure 5.

**DISCUSSION.** Following mask removals at high altitudes most individuals pass through two definite phases. The first stage can be considered as useful consciousness and may be defined as that period up to the time the subject first begins to make errors. The second is that phase in which the subject is conscious, but is so mentally confused that he either continues to make mistakes or just sits with no apparent awareness of his situation. Soon after the latter phase is reached, unconsciousness is imminent, and unless the subject is supplied with oxygen he will collapse. Most individuals lose control of muscular co-ordination at about the time that errors are made.

![Fig. 5. A comparison of the fall of average blood oxygen saturations following mask removals at four altitudes.](attachment:image)

In preliminary investigations it was found that if more than three people remained at altitudes in a low pressure chamber for a few minutes, it was impossible to retain the desired ambient oxygen pressure even though maximum ventilation was maintained in the chamber. This increase in oxygen pressure was caused by an accumulation of exhaled oxygen from the individuals wearing masks. Since the difference in oxygen tension in ambient air between 28,000 and 30,000 feet is only 4.4 mm. Hg, an increase of 1 mm. Hg is equivalent to an increase of 10 seconds in duration of consciousness at this range of altitudes. This is in agreement with conclusions of Mackenzie (1), that, “for each 1,000 feet increase in altitude between 20,000 and 32,000 feet, the duration of useful consciousness decreased by approximately twenty seconds.” At higher altitudes, errors from this source become less acute, but the importance of maintaining the exact am-
bient oxygen pressure while tests of this kind are being conducted is evident if results are to be reliable.

In an attempt to find some means of measuring useful consciousness, card naming and sorting was selected because each new card demands a new verbal response and the selection of one of four slots for placement of the card. With this procedure it was possible to establish the time when errors and mental confusion first occurred. It seems reasonable that if an individual is unable to perform this simple task of card sorting at altitude in a low pressure chamber, he certainly would be unable to carry out the more complicated duties required of him in aircraft. Experience with handwriting as a criterion of useful consciousness has indicated that many persons can continue writing legibly after mental confusion has set in. In these instances, the subject, after his mask had been replaced, often stated that he had no remembrance of having written the last few lines. This probably accounts, in part, for the fact that the average times of useful consciousness presented here are shorter than those found by investigators who have used handwriting as the measure of useful consciousness.

Figure 6 illustrates graphically the period of useful consciousness in relation to mask replacement time (imminent unconsciousness) at 28,000, 30,000, 35,000 and 38,000 feet. At 35,000 feet the time to error was 64 per cent of the total time. A study of figure 6 shows that the time to error at 35,000 feet...
follows the trend of the curve when compared with the other altitudes, but the
time to imminent unconsciousness is relatively longer. No immediate ex-
planation for this difference is apparent, since the subjects, with the exception
of the six corpsmen who acted as subjects at all four altitudes, were selected
at random from flight students.

The time of useful consciousness was reduced by two-thirds between 28,000
and 38,000 feet; it was shortened approximately one-third between 28,000 and
30,000 feet. The average reduction in time to error for each 1,000 feet for the
range of altitudes studied, was 18 seconds between 28,000 and 30,000 feet, 5
seconds from 30,000 to 35,000 feet, and 4 seconds between 35,000 and 38,000 feet.

Mackenzie (1) reported the average time of useful consciousness at 28,000 feet
to be 181 seconds with flying personnel and 154 seconds with nonflying per-
sonnel. It is difficult to account for the fact that the average of 141 seconds to
imminent unconsciousness at 28,000 feet as found in this work is shorter than
either average given for useful consciousness by Mackenzie, except on the
basis of increased oxygen partial pressure with several people in the chamber.
At 30,000 feet the same trend in comparison with data previously published is
evident. At 35,000 feet the average of 72 seconds to imminent unconsciousness,
as presented in this paper, agrees with Hemingway’s (2) average of useful con-
ssciousness. This latter comparison emphasizes the difference in end point when
the two measurements of useful consciousness are used, namely, card naming and
handwriting. Armstrong’s (3) times to coma of 90 seconds at 30,000 feet and 50
seconds at 38,000 feet agree favorably with the data here presented.

The six Hospital Corpsmen who acted as subjects at each of the four altitudes
were experienced low pressure chamber technicians and no element of fear or
anxiety entered into their performance at altitude. All other subjects were
flight students with experience in aircraft but little or no previous experience in
low pressure chambers. When the six Hospital Corpsmen are considered by
themselves, they give averages at all altitudes that are consistently 1 to 9 seconds
longer than those of the flight students.

In this discussion average times of useful consciousness have been emphasized,
and it should be highly significant for aviation personnel to know these times for
various altitudes. However, it is also important to realize that variations in
tolerance among individuals is great, and that some persons begin to make errors
in much shorter times than others.

It has been shown, (Houston, 4), that the rate of respiratory exchange plays an
important part in determining the blood oxygen saturation at 16,000 feet with
subjects breathing air. This factor of respiratory rate was not controlled or
measured in the work reported here, with the exception that subjects could not
hold their breath and call the cards as directed. However, it should be pointed
out that this factor is also an uncontrolled variable following oxygen failure in
aircraft.

In figures 1 to 4 the fall in blood oxygen saturations following the change from
100 per cent oxygen to air is graphically illustrated for each of the 4 altitudes.
These graphs indicate an initial lag in the rate of loss of oxygen from the blood
which is followed by a sharp drop and then a constant rate of fall to the time of imminent unconsciousness. The initial lag in loss of blood oxygen persists longer at the lower altitudes. In the first minute following mask removals at 28,000 feet, blood oxygen saturation had decreased an average of 26 per cent; at 30,000 feet this decrease was 33 per cent; at 35,000 feet it was 36 per cent. At 38,000 feet, the highest altitude investigated, the saturation had dropped 33 per cent in 40 seconds, or at a rate of about 50 per cent per minute.

In this investigation it was found that the average blood oxygen saturation for the 100 exposures at the time when errors were made was 64 per cent. It has been previously indicated that the average times of tremor and error are identical; average blood oxygen saturation at tremor was 64 per cent. The saturation at imminent unconsciousness was 56 per cent.

SUMMARY AND CONCLUSIONS

1. Flight students and Hospital Corpsmen were taken singly to simulated altitudes of 28,000 feet and above in a low pressure chamber and had their masks removed. While at altitude, the subject performed a simple task of card sorting and his reactions were noted and recorded. These activities were continued until unconsciousness was imminent at which time the mask was replaced and 100 per cent oxygen was administered. Blood oxygen saturations were estimated throughout the procedure with a Millikan oximeter. Ambient oxygen pressure was determined with a continuous oxygen analyzer. This procedure was repeated for 25 individuals at each of four altitudes: 28,000, 30,000, 35,000 and 38,000 feet.

2. Times to imminent unconsciousness were 141 seconds at 28,000 feet, 98 seconds at 30,000 feet, 72 seconds at 35,000 feet and 47 seconds at 38,000 feet.

3. Average times of useful consciousness, as determined by the appearance of first error in card sorting, were 110 seconds at 28,000 feet, 73 seconds at 30,000 feet, 46 seconds at 35,000 feet and 35 seconds at 38,000 feet.

4. Times of useful consciousness at altitudes above 30,000 feet plot as a straight line curve, but below this altitude the curve swings toward the horizontal as it approaches the altitude at which individuals remain conscious indefinitely.

5. The period of useful consciousness was found to be approximately \( \frac{3}{4} \) of the total time consciousness was retained.

6. Blood oxygen saturations averaged 64 per cent at the appearance of first error, and 56 per cent at imminent unconsciousness with very little variation between altitudes at the appearance of any particular anoxic symptom.

REFERENCES

(4) Houston, C. S. Unpublished data.