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EFFECTS OF EXTENDED HYPOXIA ON NIGHT VISION

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It has been well known for many years that reduction of available oxygen results in alteration of various types of visual performance. One of these changes of major importance is impairment of night vision, which was noted originally by Bert in 1878 (1). However, the effects of hypoxia on night vision became an operational problem only with the advent of high altitude flying in World War I. The major ocular problems associated with such operations were documented clearly for the first time by Wilmer and Berens in 1918 (23). Since then, a broader and more detailed understanding has developed, based largely on the work of McFarland and his colleagues, who not only quantified significant aspects of the dark adaptation function due to anoxia (hypoxia) (12,13,14,16), but also explored the serious visual impairments which result from exposure to carbon monoxide through its effect on the blood oxygen transport mechanism (17). McFarland and Forbes (15) documented also the compensatory effect of ingested glucose acting to mitigate hypoxia-induced impairment of night vision. Hecht and his co-workers (7) conducted related and very significant research on brightness discrimination, and concluded that anoxia acts mainly on the central neural mechanisms which mediate the visual process above the level of photochemical receptor activity. This conception of a central neural mechanism has been supported by the work of Maffei and Poppele (11). Other noteworthy findings have been contributed by Bunge (2) showing that the early segment of the dark adaptation function for rods is affected only slightly by hypoxia, although McFarland and Evans (13) reported a similar result for cones. Sheard (22), on the other hand, showed a relatively greater overall influence of hypoxia on rod than on cone activity during dark adaptation. Pierson (19) and Pretorius (20) recently have explored the functional effectiveness of supplemental oxygen in reducing night vision deficits at high altitude, and Schull, et al (21) have investigated

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the possibility of similar results through the use of 2,3-diphosphoglycerate.

Most recently, Ernest and Krill (5) have reported a study of fundamental significance on the effects of stimulus parameters and retinal placement of the stimulus on night vision sensitivity during hypoxia. In addition, Kobrick and Appleton (10) have demonstrated elevated dark adaptation thresholds during a 48-hour exposure to high altitude (14,700 ft.), which were accompanied by enlarged retinal blood vessels with increased tortuosity. Kobrick (9) has investigated also the luminance threshold for visibility and detection of military target objects during moderately extended hypoxia, and found significant impairments due to altitude exposure. An authoritative and concise review of night vision problems in military operations has been prepared by Carr, et al (3).

Despite the value and diversity of this information, almost all of it is based on relatively short exposure periods, usually eight hours or less; thus, little is known about the effects of chronic exposure to high altitude on night vision.

This paper describes changes in visual dark adaptation functions which were observed during a 16-day sojourn at high altitude. The data were obtained during the course of a consolidated study conducted during the summer of 1981 at a field laboratory located on the summit of Pikes Peak, Colorado (altitude = 4300 m). Various other medical and physiological measures also were taken during this study, but are reported elsewhere (6,24,25).

MATERIALS AND METHODS

Subjects

Twelve healthy male soldier volunteers, ages 18-30, were employed. They received appropriate medical screening to rule out disease or physical conditions which might be aggravated by hypoxia, and were tested also to ascertain normal vision (20/20 Snellen correctible acuity, stereopsis, phoria and color sense).

Apparatus and Procedure

Dark adaptation thresholds were measured using an adaptometer developed at the Letterman Army Institute of Research (18). The test stimuli used in this device consist of light-emitting diodes (LED's) controlled by a microprocessor. These LED's, unlike the incandescent light sources used in conventional adaptometers, emit light in relatively select segments of the visible spectrum, and in the present instrument generate light in the red and green spectral regions. Recent modifications have made it possible also to measure dark adaptation to a visual stimulus in the blue region; however, blue stimuli were not employed in this study. Although measurements of dark adaptation can be made either with or without central fixation, no fixation point was used here.

The LED sources in this device are mounted inside an integrating hemisphere and are arranged in a square pattern spanning a 20-degree retinal area. Both red and green LED's are located at each corner of the square, plus an additional red and green LED at the center position. This stimulus arrangement allows continuous sampling of a large retinal region during dark adaptation. The incorporation of both red and green stimuli in this instrument is based on the well-known observation that dark adaptation functions measured with red light invariably reach asymptotic levels more quickly than do those measured with green light. Thus, differences between red and green recovery rates are indicative of the complexity of retinal photoreceptor participation measured in selective spectral regions. Furthermore, since green light stimulates both cone and rod activity, the dark adaptation function for this region of the spectrum may well reflect both cone and rod processes along with their interaction over the course of retinal change from light adaptation to the fully dark-adapted state. Luminance levels of the LED's in this instrument are generated on the basis of a pulse modulation procedure in which the pulse width

is varied within a range of 1 to 10000 microseconds (duty cycle) at a pulse repetition frequency of 100 Hz, a value well above the flicker-fusion threshold. In this pulse domain, average quantal flux rather than peak power determine threshold level. Thus, for a constant peak power of the LED, the total average quantal flux required for threshold detection can be manipulated directly by variation of the pulse width.

The test subject first is given general instructions concerning the test procedure, the appearance of the display, and the operation of a hand-held spring-loaded control button. The subject then is seated in a darkened room, and places his head in a headrest and chin support, which then is adjusted appropriately. The test procedure is begun with exposure to a standard 5-min light adaptation period. The light then is turned off and the green LED target display is activated. At onset, the initial display is indiscernible but increases steadily in brightness. The subject depresses his button and holds it down upon first detecting the display, regardless of the presence or absence of color. Thereupon, the display immediately begins to dim steadily. When the subject can no longer detect it, he releases the control button. Another identical threshold determination procedure follows immediately, using the red LED display. Thresholds for green and red stimuli are obtained continuously in this alternating manner throughout a 20-min test period. Although additional rod adaptation could occur beyond this period of time, it was considered a sufficient sample for this experiment.

The subjects were trained intensively over a two-week period at a sea level location (Natick, Massachusetts) on all of the measures involved in the study, including two training sessions daily on the dark adaptometer. After completion of the training period, they were transported immediately to the Pike's Peak field laboratory where they resided continuously for the next 16 days. On days 2,4,6,9,11,13 and 16 of this period, they were tested on the dark adaptometer

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by the same technique used previously in sea level testing. On the 17th day, they returned to Natick, Massachusetts, for follow-up testing at sea level.

Results and Discussion

The dark adaptation functions were printed out by the adaptometer as log unit changes from initial average luminance levels of 11.66×10^{-6} lumen/cm2 sr for the red display, and 12.26×10^{-6} lumens/cm^2 sr for the green display. These individual functions for each subject in each of the successive testing sessions during continued exposure to high altitude are the data upon which analysis of the results was based. Group averages for a sequential time series of measurement points (TP) during the course of dark adaptation first were obtained separately for the last sea level practice session, and for response to both red and green stimuli for each successive testing session at altitude. The sea level testing condition was judged to be the best available index of optimum dark adaptation response of the subjects at a time when they still were unaffected by hypoxia, and was used in this analysis as a basic reference for comparison with their later performance at high altitude. The group average threshold values in response to the red stimulus display were plotted graphically and showed a moderate change in threshold levels during dark adaptation commensurate with cone response to a red stimulus. However, the data showed no evidence of impairment due to high altitude exposure; thus, further analysis of the red response data was discontinued. The group average responses to the green stimulus display were plotted similarly, and for clarity are shown as three separate graphs for the various days at altitude (Figures 1-3), although obviously they represent collectively the effects of the continuous course of altitude exposure. The sea level curve also is shown in each figure for convenient comparison.

Figures 1-3 about here

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It can be seen in Figures 1-3 that the sensitivity thresholds became noticeably elevated during the course of altitude exposure, as compared to performance at sea level. These differences appear to have been greatest overall during the period from approximately 1-1/2 to 10 minutes of the dark adaptation process. Note that this time zone would include the normal occurrence of the rod-cone shift (usually at around 5-7 minutes), of which there is some evidence in these curves at about 5-1/2 minutes in the sea level curve and to a lesser degree in the altitude exposure curves. It can be seen also that the curves for successive days of exposure show considerable separation from the sea level performance curve in Figures 1 and 2, but somewhat less in Figure 3; also, the first half (approximately 0-11 min.) of these curves in general shows more separation than does the last half (11-20 min). The lesser separations noted in Figure 3 compared to Figures 1 and 2 may possibly be explained by the fact that on day 11 the subjects were provided an eight-hour period of rest and relaxation at a lower altitude (approximately 3200m). The data points for day 11 represent the results of a test session which was conducted immediately upon their return that evening to the high altitude laboratory. It can be seen that the subsequent daily test functions reflect an increasing impairment of dark adaptation once again, although the study was terminated before a degree of impairment comparable to the previous level could be developed once more. However, the data derived from this departure from schedule suggest that the effects of high altitude on dark adaptation are rapid and sensitive, and apparently are related closely to the level of altitude being experienced. It is particularly important to observe that a reduction in elevation of only 1100m was still sufficient to produce noticeable recovery in the dark adaptation function.

In order to assess the statistical significance of the differences of the daily functions due to continued altitude exposure, a separate analysis of variance (two-way, repeated measures, treatments x subjects type) (8) was conducted for each of four arbitrarily chosen segments of the dark adaptation function (0-1.45 min; 1.45-2.91 min; 2.91-10.91 min; 10.91-20.00 min). Four separate analyses were chosen in preference to a single overall analysis as a more sensitive analytic approach which would be suited better to the obviously changing degrees of difference among/the daily curves at various segments of the function. The choice of zones for separate analysis was based upon visual inspection of the curves, and also upon adjacency of the data point locations which the adaptometer provided; hence, the fractional values of the time zones which resulted. A summary of the F values and significance levels derived from these analysis is presented as Table I.

Table I about here

It can be seen in Table I that all three main effects (successive days at altitude, sequence of measurement points in each time segment, and differences among subjects) were all highly significant, except for the altitude duration effect in the fourth segment (P= .05). Although they are not shown, all of the calculated simple interactions among the main effects proved to be highly significant, as well. Thus, it would appear that hypoxia in this study exerted a critical and systematically degrading influence on the efficiency of dark adaptation, and affected the entire course of the function, although apparently the major effects occurred during the first ten minutes. It would seem from Figures 1-3 that these hypoxic effects peaked during days 6-9, although one still must question what effect the respite on day 11 actually had with respect to what the eventual outcome might otherwise have been.

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Certainly this interruption of exposure is a graphic indication of the sensitivity of response of the visual system to prevailing ambient oxygen levels. This occurrence, in fact, is corroborated by our personal experience in other studies in which return to sea level often was observed to result in rapid recovery of function in a variety of other visual tasks.

An inspection was made also of the actual mean differences between thresholds for sea level and for successive days of altitude exposure at the various measurement points during the time course of dark adaptation. These differences were found on the average to be about 0.5 log unit over the first half of the function, the period during which the larger impairments occurred; however, individual subjects often showed peak impairments of 1.0 log unit, or greater. Thus, the observed impairments generally were highly significant in a statistical sense, but also were large enough in real terms to constitute a practical problem for the performance of actual tasks involving night vision at this altitude.

The statistical significance of the differences between the group mean thresholds for sea level and for the various altitude exposure durations then was evaluated, using the Cicchetti Multiple Range Test (4) based on a critical difference derived from the appropriate analysis of variance which included the means involved. A summary of the significance levels resulting from these tests is given in Table II.

Table II about here

It is clearly evident in Table II that the major hypoxic impairments were almost all included within roughly the first half (0-7.27 min) of the dark adaptation function, and involve mean differences of very high significance (P < .0001) in almost all cases. Furthermore, the influence of hypoxia apparently was negligible

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until the fourth day at altitude, whereupon highly significant impairments developed quite rapidly. Table II also shows very clearly the effects of the aforementioned change in altitude exposure to 3200m on day 11, as well as the resumption of impairment following return to the higher elevation. It would appear also that the latter segment of the function was relatively unaffected. This might seem to be contradicted by the high significance levels of all four analyses of variance which encompassed the entire dark adaptation function. However, this can be explained by the fact that the four segments of the dark adaptation function to which the respective analyses of variance were applied all included some degree of significant change due to altitude, except the last zone for which the F level was only of borderline significance (P=.05). These four zones of data are indicated in Table II. It is appropriate here to note that the differences between measurement points in each zone of the function were all highly significant, indicating that the rates of change of the functions were sizable; also, that they probably were not differentially influenced by hypoxia in comparison with sea level performance.

It should be noted also that the present results would seem to contradict the findings of Bunge (2), to be corroborated later by Ernest and Krill (5), that the early segment of the dark adaptation function was unaffected by hypoxia. This disagreement probably can be explained by the differences in duration of hypoxia exposure involved in the three studies. Thus, although the early segment seems to be unaffected for shorter periods of exposure (up to about eight hours), longer periods of exposure such as those involved in the present study appear to affect the entire dark adaptation function.

One of the most important aspects of the present results is the continued impairment of night vision which prevailed during sustained hypoxia, but which

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recovered very rapidly and substantially when hypoxia was reduced, although not eliminated. This must be considered a significant demonstration of the sensitive dependence of the dark adaptation function on availability of oxygen, both in susceptibility to impairment and in recovery capability, even after extended hypoxia. The clear implication of this relationship for practical operations is that supplemental oxygen is a necessary requirement for essential operations which involve night vision. This is especially important, since apparently very little functional recovery can be expected over the course of chronic hypoxia exposure. On the positive side, supplemental oxygen,when supplied, should be an effective and rapid-acting remedy for reducing night vision impairments in high altitude operations.

A final point for consideration is the distinct difference in response to red and green waveband stimulation which was observed in this study. Such a sizable difference probably should not be expected hypothetically, in view of the collected findings and conclusions of Bunge (2), McFarland and Evans (13) and Sheard (22), which seem to imply only a slight influence of hypoxia on the cone photoreceptors. One possible explanation (proposed by Dr. Harry Zwick, Letterman Army Institute of Research) is that due to their different geographic distribution in the retina, green-sensitive receptors receive a greater blood supply than do red-sensitive receptors because of differences in the density of the retinal vascular bed. Thus, green receptors should be more responsive to changes in blood-delivered oxygen. Investigation of this issue remains for future research.

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TABLE I

Summary of Fisher's F Tests and Significance Levels (P)
For the Various Altitude Treatment Effects During Four
Time Segments of the Dark Adaptation Function

Time Segment (Min.)	Altitude Duration Effect (days)		Time Point Sequence (Min)		Subjects Effect	
	F	P	F	P	F	P
0 - 1.45	2.66	.02	281.49	<.00001	7865.05	<.00001
1.45 - 2.91	3.68	.002	60.08	<.00001	2108.28	<.00001
2.91 - 10.91	2.38	.03	112.47	<.00001	1929.26	<.00001
10.91 - 20	2.09	.05	9.68	<.00001	1356.03	<.00001

TABLE II

Summary of Level of Significance of Differences
Between Group Mean Dark Adaptation Thresholds
For Sea Level and Altitude Exposure Durations*

Test Time (Min)	Days of Altitude Exposure							Anal. of Var. Zone
	Day 2	Day 4	Day 6	Day 9	Day 11	Day 13	Day 16	
0.36		XX		X				I
0.72		XX		X				I
1.09		XX	XX	XX				I
1.45		XX	X	XX			XX	I
1.82			X	XX			XX	II
2.18		XX	XX	XX			XX	II
2.55		XX	X·	XX			XX	II
2.91		XX	XX	XX			XX	II
3.27	XX	XX	XX	XX	X	XX	XX	II
3.64	X	XX	XX	XX		X	XX	III
5.45		XX	XX	XX				III
7.27		XX	XX	XX		XX	XX	III
9.09								III
10.91								III
12.73	X							IV
14.55								IV
16.36							X	IV
18.18								IV
20.00	X							IV

* Based on Cicchetti Multiple Range Test (4)
   X = P .05
   XX = P .00001

Abstract

The effects of sixteen days of sustained hypoxia (4300m equivalent) on the dark adaptation threshold function were studied. Twelve male subjects were measured periodically (days 2,4,6,9,11,13,16 of exposure) over a 20-min test period for both red and green stimuli using a new computerized dark adaptometer. Comparison with sea level performance showed negligible elevations of thresholds for red response, but highly significant impairment of green response $(P < .00001)$ over almost the entire dark adaptation function. These losses peaked between the sixth and ninth day followed by little recovery, except at the eleventh day when the subjects descended briefly to 3200m elevation. Impairments developed rapidly again upon return to the original higher altitude. The results differ from previous published findings based on shorter exposure periods which showed only slight impairments of the early segment of dark adaptation. Implications of the results are discussed.

Index words:

Hypoxia

Anoxia

Night vision

Dark adaptation

Extended hypoxia

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Figure Captions

Figure 1.   Group mean dark adaptation thresholds on days 2 and 4 of altitude
            exposure compared to sea level performance.

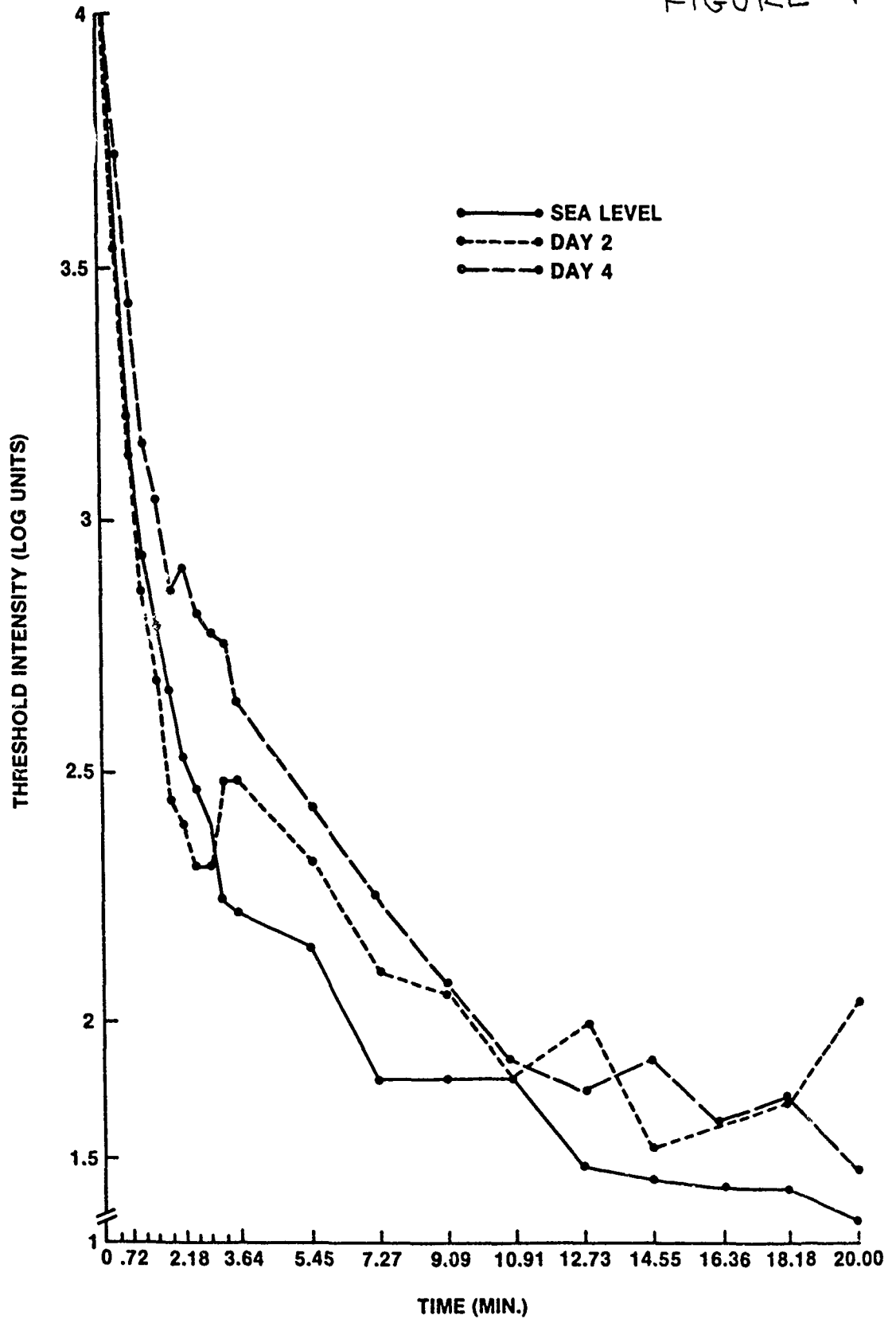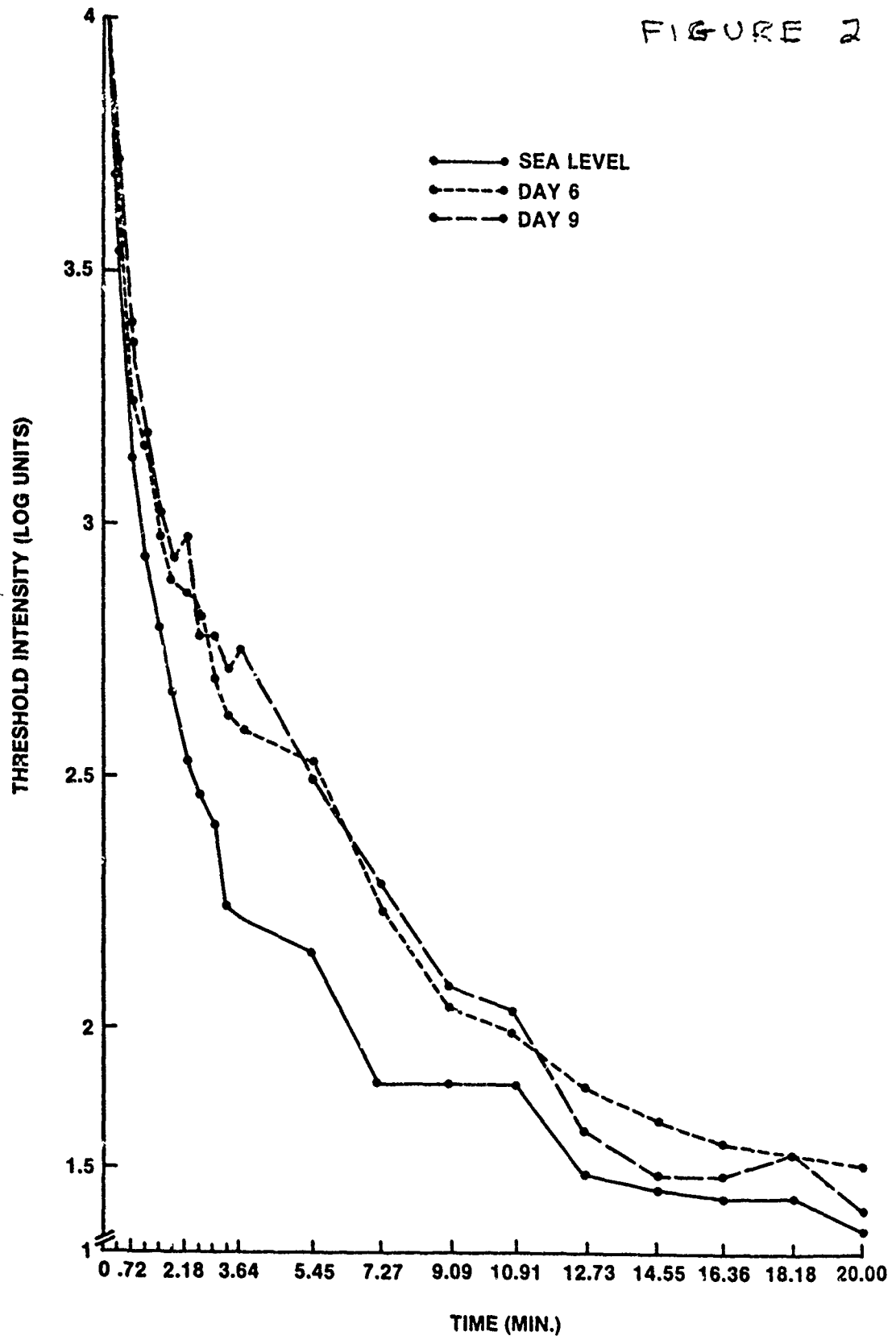Figure 2.   Group mean dark adaptation thresholds on days 6 and 9 of altitude
            exposure compared to sea level performance

Figure 3.   Group mean dark adaptation thresholds on days 11, 13 and 16 of
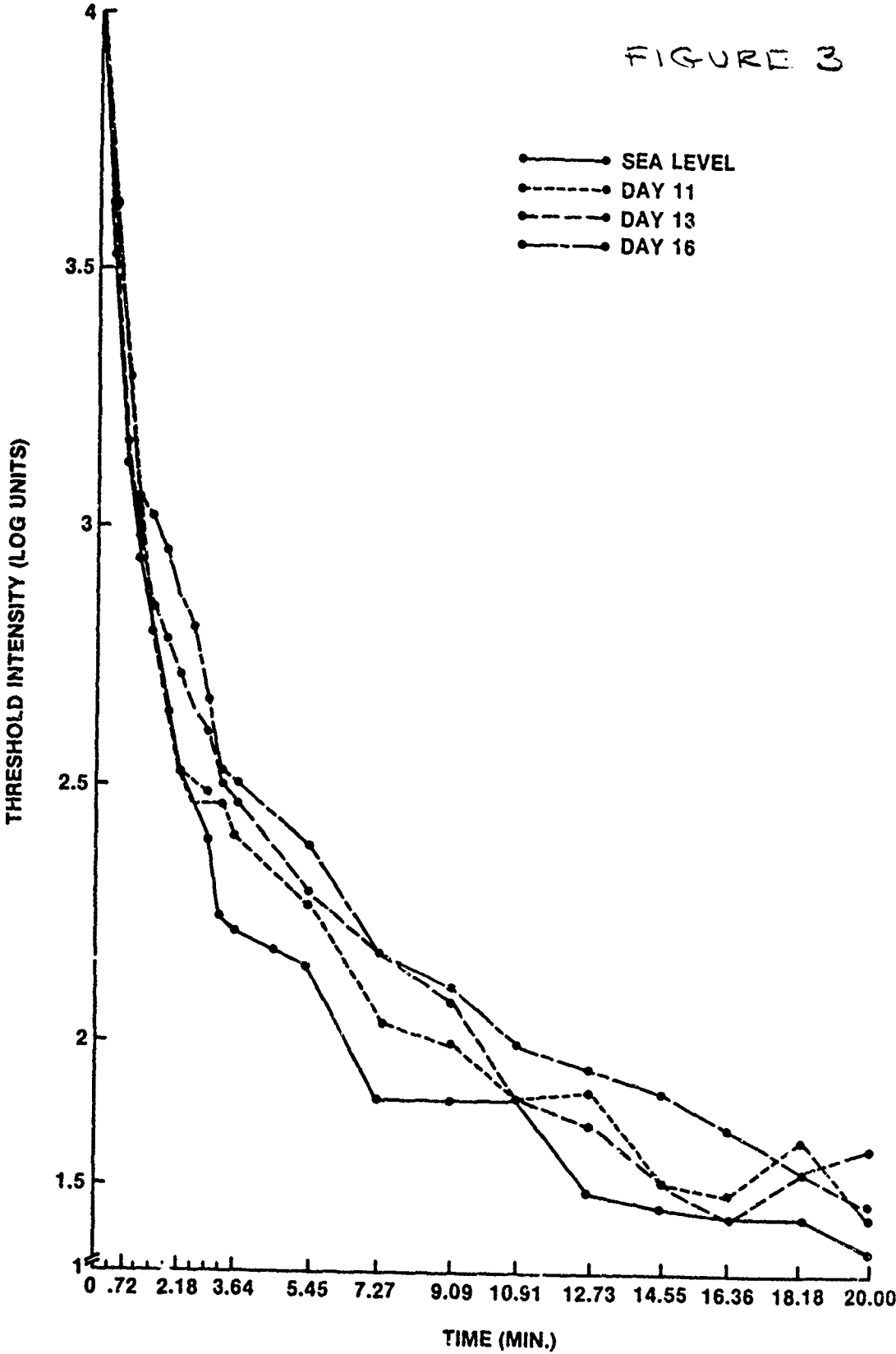   altitude exposure compared to sea level performance

FIGURE 1

FIGURE 2

FIGURE 3