THE COST TO THE CENTRAL NERVOUS SYSTEM OF CLIMBING TO EXTREMELY HIGH ALTITUDE

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Abstract To assess the possibility that climbing to extremely high altitude may result in hypoxic injury to the brain, we performed neuropsychological and physiologic testing on 35 mountaineers before and 1 to 30 days after ascent to altitudes between 5488 and 8848 m, and on 6 subjects before and after simulation in an altitude chamber of a 40-day ascent to 8848 m.

Neuropsychological testing revealed a decline in visual long-term memory after ascent as compared with before; of 14 visual items of information on the Wechsler Memory Scale, fewer were recalled after ascent by both the simulated-ascent group (a mean [±SD] of 10.14±1.68 items before, as compared with 7.00±3.35 items after; $P<0.05$) and the mountaineers (12.33±1.96 as compared with 11.36±1.88; $P<0.05$). Verbal long-term memory was also affected, but only in the simulated-ascent group; of a total of 10 words, an average of 8.14±1.86 were recalled before simulated ascent, but only 6.83±1.47 afterward ($P<0.05$). On the aphasia screening test, on which normal persons make an average of less than one error in verbal expression, the mountaineers made twice as many aphasic errors after ascent (1.03±1.10) as before (0.52±0.80; $P<0.05$). A higher ventilatory response to hypoxia correlated with a reduction in verbal learning ($r = -0.88$, $P<0.05$) and with poor long-term verbal memory ($r = -0.99$, $P<0.01$) after ascent. An increase in the number of aphasic errors on the aphasia screening test also correlated with a higher ventilatory response to hypoxia in both the simulated-ascent group ($r = 0.94$, $P<0.01$) and a subgroup of 11 mountaineers ($r = 0.59$, $P<0.05$).

We conclude that persons with a more vigorous ventilatory response to hypoxia have more residual neurobehavioral impairment after returning to lower elevations. This finding may be explained by poorer oxygenation of the brain despite greater ventilation, perhaps because of a decrease in cerebral blood flow caused by hypocapnia that more than offsets the increase in arterial oxygen saturation. (N Engl J Med 1989; 321:1714-9.)

BOTH transient and long-lasting neurobehavioral impairments have been found in a group of young, fit mountaineers after an expedition to climb Mount Everest (altitude, 8848 m; barometric pressure, about 34 kPa [253 mm Hg]).[1] Before and after the expedition, these climbers were given a variety of neuropsychological tests known to be sensitive to the integrity of cortical function. The transient effects from exposure to extremely high altitude were found to include mild deterioration in the ability to learn, remember, and express information verbally. These impairments were present during the first three days after the return to low altitude but not one year later. A bilateral reduction in the ability to maintain the speed of finger tapping persisted one year later. This long-lasting deficit was consistent with the observations of Regard et al.[2] Mild impairment in memory has also been observed after climbs in the Himalayas without supplemental oxygen.[2,3] Using similar tests, however, Clark et al.[4] and Jason et al.[5] found no evidence of cerebral impairment in subjects tested 16 to 221 days after Himalayan climbs to maximal altitudes ranging from 5335 m to 8848 m.

We report the neurobehavioral changes observed in 35 mountaineers who ascended to more than 5488 m (barometric pressure, 51 kPa [380 mm Hg]) and in 6 participants in a study simulating high altitude (Operation Everest II) who underwent gradual decompression in an altitude chamber until the barometric pressure was the equivalent of that at the summit of Mount Everest. Published observations show a significant correlation between the ventilatory response to hypoxia and climbing performance such that persons with a higher hypoxic ventilatory response tend to function better at high altitude.[6-8] We hypothesized that persons with a higher ventilatory response to hypoxia and therefore better arterial oxygenation would be less susceptible to neurobehavioral impairment after exposure to extremely high altitudes.

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METHODS

Subjects Undergoing Decompression

Six members of the Operation Everest II team, all healthy men 21 to 31 years of age, lived in a hypobaric chamber at normal room temperatures during 40 days of progressive decompression designed to simulate barometric-pressure conditions during an ascent of Mount Everest. The selection of subjects and the conditions of the experiment, including the rate of ascent, have been described elsewhere.[9] The subjects were informed that we were evaluating the effects of the lack of oxygen at high altitude on brain function. Consent was obtained before the initial testing. The study was approved by the human subjects review committee of the University of Washington, Seattle.

Two days before the subjects entered the chamber and on the day after recompression to the normal barometric pressure at sea level from an inspired partial pressure of oxygen equivalent to that found at 8848 m of altitude, the subjects were given the following standard neuropsychological tests[10]: logical memory passages, visual designs, and paired-associate learning tasks from the Wechsler Memory Scale[11]; Buschke's Selective Reminding Test with a 20-minute delayed recall[12]; the vocabulary, digit-span, and digit-symbol subtests of the Wechsler Adult Intelligence Scale — Revised[13]; the verbal-fluency subtest of the Repeatable Cognitive–Perceptual–Motor Battery[14]; and the trails B, finger-tapping, and aphasia screening tests from the Halstead–Reitan Neuropsychological Test Battery.[15]

Standard published procedures were used for administration and scoring, with several exceptions. The vocabulary test was divided

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into two tests, one composed of the odd-numbered items and the other of the even-numbered items, in order to provide two separate but comparable tests. On the aphasia screening test, the verbal expressive items were scored from 0 (normal) to 4 (grossly abnormal) on the basis of criteria developed for the study; in the same test, the four drawings were scored from 0 (accurate) to 2 (very inaccurate), according to guidelines established by Russell et al.,[16] with modifications. Scoring procedures for the verbal and visual motor components of the aphasia screening test are available on request. Changes in neurobehavioral function were calculated by subtracting the scores obtained during the initial testing from those obtained subsequently.

The partial pressures of oxygen and carbon dioxide in arterial blood (PaO_2 and $PaCO_2$) were measured at sea-level pressure before the simulated ascent and at barometric pressures equivalent to those found at altitudes of 8100 m and 8848 m; no blood gas measurements were obtained after the return to sea-level conditions. The ventilatory response to breathing a hypoxic gas mixture under conditions of constant $PaCO_2$ was assessed in duplicate by a technique previously described[17]; the hypoxic ventilatory response was expressed as the slope $\Delta\dot{V}_E/\Delta SaO2$, where $\dot{V}_E$ is expired ventilation measured in liters per minute at body temperature and ambient pressure, and saturated with water vapor, and SaO_2 is the percentage oxygen saturation of hemoglobin in arterial blood as measured by ear oximetry.

Table 1. Comparison of the Performance of 6 Subjects from Operation Everest II and 35 Mountaineer Subjects on Neuropsychological Testing before and after Exposure to Hypoxia.*

	Operation Everest II		Z	Mountaineers		Z
	Before	After		Before	After	
	mean ±SD			mean ±SD		
Selective Reminding Test[12] (no. of words recalled, of 10)	8.14±1.86	6.83±1.47	2.20†	7.41±2.15	7.35±2.50	0.06
Aphasia screening test[15]						
Visual motor errors	1.71±1.25	2.83±1.33	2.02†	0.58±0.71	0.58±0.87	0.31
Verbal expressive errors	6.17±3.60	7.50±3.39	0.10	0.52±0.80	1.03±1.10	2.15†
Wechsler Memory Scale[11] (visual–long-term: no. of items recalled, of 14)	10.14±1.68	7.00±3.35	2.02†	12.33±1.96	11.36±1.88	2.01†
Finger tapping[15] (mean no. of taps per trial in five 10-second trials)						
Right hand	51.57±2.70	46.67±6.53	1.68	55.88±4.60	50.18±7.75	3.44‡
Left hand	44.29±4.79	44.50±6.47	0.67	48.91±5.39	46.06±7.24	2.09†

*Lower scores on the tapping and memory tests and higher scores on the aphasia screening test imply poorer performance.
†P<0.05. ‡P<0.01.

Mountaineers

Thirty-four men and one woman, from 24 to 45 years of age, completed neuropsychological testing before and after one of five mountaineering expeditions involving climbs to altitudes of more than 5488 m: the 1982 China expedition to Mount Everest (6 subjects), the 1982 Tirich Mir expedition to Pakistan (5 subjects), the 1983 expedition of Men and Women on Everest (2 subjects), the 1984 Ultima Thule expedition to Mount Everest (4 subjects), and the 1981 American Medical Research Expedition to Everest (AMREE) (18 subjects). The neurobehavioral assessment of the AMREE subjects has been reported elsewhere, but not the correlation with hypoxic ventilatory response.[1] Neuropsychological testing was administered to these subjects at low altitude (below 1000 m) several weeks before ascent and within one month of the descent from high altitude. All but one of the AMREE subjects were tested within one week of descent.[1] The tests administered were the Halstead–Reitan Neuropsychological Test Battery,[15] the Repeatable Cognitive–Perceptual–Motor Battery,[14] the Selective Reminding Test,[12] and the Wechsler Memory Scale.[11] Among the group of 35 mountaineers, the hypoxic ventilatory response was measured only in the 18 AMREE subjects, and results of such testing are therefore limited to this subgroup. Because an oximeter was not available for all the tests performed at sea level before the expedition, the hypoxic ventilatory response was quantified as $\Delta\dot{V}_{40}$, liters · min^{-1} or the difference in minute ventilation between breathing a hyperoxic gas mixture and breathing a progressively hypoxic gas mixture for 7 to 10 minutes until an end-tidal partial pressure of oxygen of approximately 40 mm Hg was reached.

Data Analysis

The data were analyzed with the Wilcoxon signed-rank test[18] to determine the significance of the changes in performance on neuropsychological testing before and after exposure to hypoxia. Because the subjects from Operation Everest II and the AMREE subjects were also tested at three intervening times, practice effects may have influenced the performance on testing after exposure, biasing the results toward apparently improved performance. Thus, the demonstration of adverse effects from hypoxia at high altitude may underestimate the severity of neurobehavioral impairment. Physiologic measures were related to neuropsychological outcomes by means of Pearson product-moment correlations.[18] Two-tailed tests of significance were used throughout.

Results

Neurobehavioral Outcomes

Among the subjects of Operation Everest II, there were no significant differences in performance on the vocabulary test before and after exposure to hypoxia; as a measure of stored verbal learning, the test is known to resist the effects of many stressors of brain function.[19] Attention and efficiency in problem solving (as assessed by the trails B and digit-symbol subtests) and verbal fluency were maintained as well, suggesting no generalized impairment in functioning due to hypoxic stress. No changes in performance were seen in these subjects on the paired-associate learning task or the digit-span test. The subjects required the same number of trials to learn a list of 10 words on the Selective Reminding Test, but their recall of the words 20 minutes later was poorer after the recompression ($P<0.05$) (Table 1).

Decrements in visual motor performance on the aphasia screening test ($P<0.05$) were observed after hypoxic exposure in the subjects from Operation Everest II but not in the 35 mountaineers (Table 1). The types of stimuli presented to the subjects and examples of the associated construction errors are shown in Figure 1. After the exposure to simulated high altitude, these constructional deficits were accompanied by a significant decay in long-term visual memory among the subjects from Operation Everest II ($P<0.05$) and the mountaineers ($P<0.05$) (Table 1). In testing after exposure, the constructional deficits were associated with decay in long-term visual memory in the same six subjects ($r = -0.85$, $P<0.05$), suggesting a possible effect on the functioning of the occipital and parietal lobes.

A statistically significant decrement in the motor speed of the right and left hands occurred among the

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mountaineers but not among the subjects from Operation Everest II, perhaps because of the smaller sample (Table 1). When the AMREE subjects were tested one year later, they had persistent decrements in this motor function.[1]

Deficits in verbal expression may be a characteristic transient consequence of severe, sustained hypoxia. Such deficits were present among the mountaineers after their expeditions ($P<0.05$; Table 1). On testing within a week of descent, the AMREE subjects had errors of expressive language that included errors in reading, writing, calculation, spelling, and pronunciation, as well as confusion with regard to body parts.[1] Although the somewhat greater degree of aphasic impairment in the subjects from Operation Everest II after exposure was not statistically significant, two of these subjects had an obvious difficulty in finding words that was not present before exposure to simulated high altitude.

Physiologic Correlations

Measures of oxygenation and ventilation in the subjects from Operation Everest II at simulated extreme altitude are shown in Table 2. Arterial hypoxemia was severe, particularly during exercise, when the average PaO_2 fell below 30 mm Hg. Among these subjects, a higher hypoxic ventilatory response was significantly correlated with an increased impairment on the Selective Reminding Test (number of trials and degree of recall), the Wechsler Memory Scale (immediate verbal recall), and aphasic errors (Table 3). Improved arterial oxygenation (higher PaO_2 and arterial oxygen saturation) and lower $PaCO_2$ at 8100 m and 8848 m, expected in those with a higher hypoxic ventilatory response, were also associated with worse neurobehavioral outcomes (Table 3). One additional correlation, higher levels of maximal oxygen consumption, was significantly related to better verbal learning and recall in regard to total amount learned ($r = 0.98$, $P<0.001$), number of words remembered on the last trial ($r = 0.87$, $P<0.05$), and number of words retrieved 30 minutes later ($r = 0.88$, $P<0.05$); the range over which the maximal oxygen consumption varied was small, and no significant relation was observed between it and the hypoxic ventilatory response. Finally, poorer oxygenation during sleep was associated with poorer neurobehavioral functioning subsequently (Table 4). In 11 AMREE subjects, higher values for hypoxic ventilatory response were correlated with an increase in the number of aphasic errors ($r = 0.59$, $P<0.05$) in testing before and after exposure to hypoxia (Fig. 2).

Table 2. Measures of Hypoxic Ventilatory Response, Arterial Oxygenation (SaO_2 and PaO_2), and Alveolar Ventilation ($PaCO_2$) in the Six Subjects of Operation Everest II.*

Physiologic Measure	Equivalent Altitude (m)	Variable	Value†
Hypoxic ventilatory response	0	Rest	−0.22±0.1
	8100	Rest	−0.35±0.1
SaO_2 (%)	8100	Rest	67.8±5.0
		Exercise	58.3±2.7
	8848	Rest	58.0±4.5
		Exercise	50.5±2.7
PaO_2 (mm Hg)	8100	Rest	36.6±2.2
		Exercise	33.1±1.2
	8848	Rest	30.3±2.1
		Exercise	27.6±0.6
$PaCO_2$ (mm Hg)	8100	Rest	12.5±1.1
		Exercise	11.4±1.4
	8848	Rest	11.2±1.7
		Exercise	9.6±1.8

*SaO_2 denotes arterial oxygen saturation, PaO_2 partial pressure of oxygen in arterial blood, and $PaCO_2$ partial pressure of carbon dioxide in arterial blood. Hypoxic ventilatory response was measured as isocapnic, according to the formula $\Delta \dot{V}_E/\Delta SaO_2$, where $\dot{V}_E$ is the expired volume per minute. Exercise was measured at 120 W.

†Values are means ±SEM of five measurements.

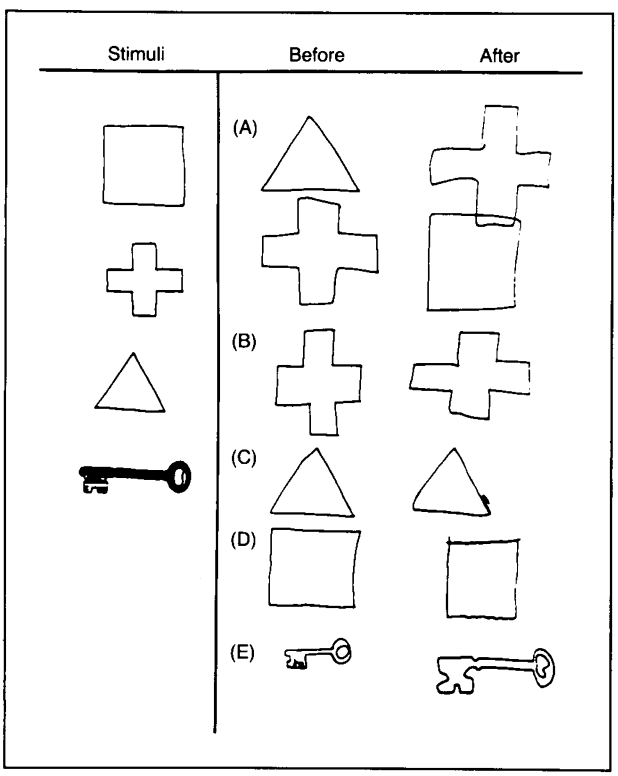

Figure 1. Selected Drawings by the Subjects of Operation Everest II at Testing before and after Exposure to Hypoxia.

After exposure, the subjects had difficulty planning ahead and organizing the figures correctly on the page (note overlap, Panel A), reproducing the proportions of the cross accurately (Panel B), and obtaining accurate closure of the triangle (Panel C). One subject had a pronounced hand tremor after the expedition, as well as difficulty with closure (Panel D), and another subject could not maintain the spatial organization of the notches on the key (Panel E).

Discussion

We identified impairments in neurobehavioral performance after a return to low elevations in persons exposed to the hypoxia of extremely high altitudes (actual and simulated). We attribute the impairments to brain dysfunction resulting from the lack of oxygen at altitude. Although environmental factors such as cold, ultraviolet radiation, uncertainty, and fear may affect the results of certain psychological tests, the subjects from Operation Everest II did not experience

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Table 3. Significant Correlations in the Subjects from Operation Everest II between Neurobehavioral Impairment after Exposure to Hypoxia and Measures of Hypoxic Ventilatory Response.*

Physiologic Measure/ Neuropsychological Test or Scale	Equivalent Altitude (m)	No. of Subjects	r
Hypoxic ventilatory response			
Selective Reminding Test (sum recall)	0	6	−0.82†
Wechsler Memory Scale			
Paired associate (immediate recall)	0	6	−0.88†
Paired associate (delayed recall)	0	6	−0.99‡
Verbal (immediate recall)	8100	6	−0.86†
Aphasia screening test	8100	6	0.94‡
SaO_2			
Digit symbol	8100	6	−0.85†
Finger tapping (left hand)	8100	6	0.85†
PaO_2			
Vocabulary	8100	6	−0.89†
Finger tapping (left hand)	8848	4	−0.98†
Wechsler Memory Scale (no. of trials)	8848	4	0.99†
$PaCO_2$			
Digit span	8848	4	−0.99‡

*SaO_2 denotes arterial oxygen saturation, PaO_2 partial pressure of oxygen in arterial blood, and $PaCO_2$ partial pressure of carbon dioxide in arterial blood. Arterial blood gas measurements were obtained in only four of the six subjects at 8848 m. For all values shown except those for finger tapping (left hand) at 8100 m, greater neurobehavioral impairment is correlated with higher hypoxic ventilatory response.

†$P<0.05$. ‡$P<0.01$.

these additional stresses. Because their neurobehavioral outcome was similar to that of the mountaineers, the results cannot be attributed to environmental factors associated with extremely high altitude.

In ascribing these neurobehavioral changes to hypoxia, other possible variables must be considered. When a large number of neurobehavioral and physiologic correlations are attempted, chance alone will yield some significant differences. However, all but one of the statistically significant correlations we observed (Table 3) related greater neurobehavioral impairment to a higher hypoxic ventilatory response, suggesting that the changes were not spurious. Fatigue or other circumstances related to the return from an arduous mountain experience or from confinement in a hypobaric chamber could have affected test performance. Two factors argue against such nonspecific causes for the observed neurobehavioral changes. First, fatigue would have been associated with a generalized impairment of performance that would have been particularly evident on timed tests such as the trails B and digit-symbol tests.[20,21] Second, the observations of the subjects from Operation Everest II were obtained on the first day after leaving the hypobaric chamber, whereas in the case of the mountaineers, testing was performed 1 to 30 days after descent. The similarity of the findings in the real and simulated settings of high altitude indicates that within these limits the variability in the timing of the data collection after exposure to hypoxia was not a critical factor.

Two previous studies failed to find a significant degree of impairment in high-altitude mountain climbers.[4,5] These results may have been due to a lower level of hypoxic stress (a lower mean altitude, a shorter exposure, or both) and perhaps also to the fact that testing was performed later after the expedition had ended; the latter explanation would imply a fairly rapid recovery from many of the changes we observed. Several studies have noted changes similar to those reported here. Of particular relevance are the findings of Regard et al.,[2] who assessed the higher cortical function of eight world-class mountaineers 2 to 10 months after the last of repeated exposures to altitudes above 8000 m without use of supplemental oxygen. Five persons had mild impairment of concentration, short-term memory, and cognitive flexibility. The three who were affected most severely also had alterations detectable on electroencephalography. The degree of impairment did not correlate with age, total time above 8000 m, or the time since exposure to high altitude. Like the deficit in finger tapping observed one year after exposure to high altitude in the AMREE subjects, these long-lasting changes fuel the historical concern that the exposure of normal humans to extremes of earthbound hypoxia may result in permanent brain injury, and indeed that such injury may occur even without obvious evidence of central nervous system dysfunction during the time at high altitude. Evidence of similar neurobehavioral impairment has also been reported in association with the chronic hypoxemia seen in some patients with chronic obstructive pulmonary disease.[22]

Susceptibility to the hypoxia of high altitude varied greatly among the subjects. One factor that may account for some of the variability is the hypoxic ventilatory response. We offer two possible explanations for this unexpected correlation of a high hypoxic ventilatory response with greater neuropsychological impairment. First is the possibility that although the subjects with a higher hypoxic ventilatory response had a greater arterial oxygen saturation under normal resting conditions, their oxygen saturation may be lower than that in subjects with a lower hypoxic ventilatory

Table 4. Significant Correlations between Blood Oxygen Saturation during Sleep at 8100 m and Subsequent Neurobehavioral Impairment in Five of the Six Subjects from Operation Everest II Who Reached 8848 m.

Measure of Oxygen Saturation	Neuropsychological Measure*	r
Mean	Verbal delayed recall	−0.99†
50% of the night	Finger tapping (left hand)	−0.95‡
75% of the night	Verbal delayed recall	−0.89‡
% of night ≤50§	Verbal delayed recall	0.98†
% of night ≤50§	Finger tapping (left hand)	0.88‡

*Measures of verbal delayed recall were made with use of the Wechsler Memory Scale.

†$P<0.01$.

‡$P<0.05$.

§Average saturations were computed minute by minute throughout the night. These values were rank-ordered from highest to lowest. The values used in the calculations represent the highest saturation seen during 50 percent and 75 percent of the night, respectively. In all instances, neurobehavioral impairment was associated with a lower mean oxygen saturation as averaged over specific periods during sleep.

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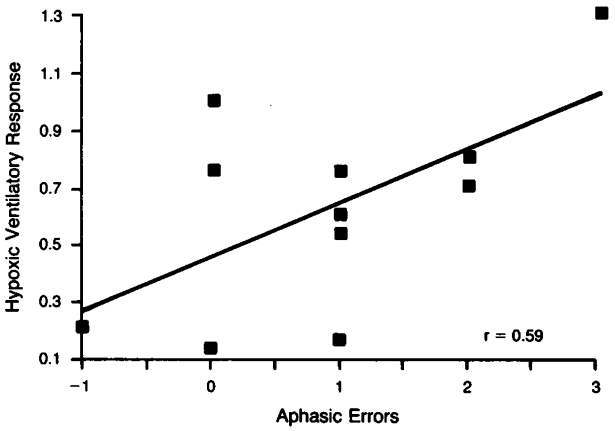

Figure 2. Correlation of Hypoxic Ventilatory Response and Number of Aphasic Errors in the AMREE Subjects.

Persons with a higher hypoxic ventilatory response had more aphasic errors as measured on the aphasia screening test.

response under other circumstances, such as during exercise or sleep. At high altitude, an increase in work is associated with a decline in arterial oxygen saturation, because of the limitation of gas transfer in the lung,[23-25] but even so, persons with a high hypoxic ventilatory response have a higher arterial oxygen saturation during work than do those with a low response.[7] During sleep at high altitude, periodic breathing (Cheyne–Stokes respiration) is common and is accompanied by swings in arterial oxygenation, the lowest values occurring at the ends of the apneic pauses. Although the data from Operation Everest II do not show a significant correlation between periodic breathing during sleep and the hypoxic ventilatory response while awake, periodicity has been reported to be greater in persons with a higher hypoxic ventilatory response.[26] Therefore, these persons may have brief moments of severe arterial hypoxemia during apnea, even though their maximal or mean level of oxygenation could exceed that of persons with a lower hypoxic ventilatory response and less periodicity. During sleep at extremely high altitude, transient desaturation during apnea may reach levels low enough to cause brain injury. Among the subjects of Operation Everest II, those with lower average arterial saturation and more sleep time spent at lower saturation (Anholm JD: personal communication) had greater impairment of verbal delayed recall and finger tapping than those better oxygenated during sleep (Table 4). Because neurobehavioral impairment was also associated with a higher hypoxic ventilatory response, one might anticipate a correlation between the hypoxic ventilatory response and the extent of desaturation in the apneic periods during sleep, but no statistically significant relation of this kind was found among the five persons in whom sleep measurements were made at 8100 m.

Another possibility is that the lower resting $PaCO_2$ in persons with a high hypoxic ventilatory response compromised brain function.[24,25] Although the additional respiratory alkalosis may have affected the metabolic function of the brain directly or lowered the rate of release of oxygen from hemoglobin because of the leftward shift of the oxyhemoglobin-dissociation curve, a more plausible explanation is that hypocapnic vasoconstriction of the cerebral blood vessels decreased the flow of blood and hence the delivery of oxygen to the brain. Although noninvasive gated-Doppler measurements of blood velocity in the middle cerebral artery were obtained while the subjects of Operation Everest II were at rest at simulated high altitude, the measurements did not correlate either with the hypoxic ventilatory response or the neurobehavioral outcomes. No information was obtained about whether the cerebral blood flow decreased in association with the additional short-term drop in $PaCO_2$ during exercise (Table 2). Nor do we know how much the cerebral blood flow might decrease in the presence of acute hypocapnia during exercise, when the resting $PaCO_2$ is 8 to 12 mm Hg and the PaO_2 is near 30 mm Hg. On the basis of the average decrease in cerebral blood flow known to accompany hypocapnia under normal conditions at sea level, only a small additional decrement would be needed in order to more than offset the rise in arterial oxygen saturation associated with hyperventilation at the summit of Mount Everest. A similar explanation may also pertain to the interesting observation that visual motor speed and memory improved when patients with chronic hypoxemia who received long-term oxygen therapy had their supply of supplemental oxygen temporarily discontinued.[27]

Interestingly, persons with a high hypoxic ventilatory response, who appear more impaired after exposure to extremely high altitude, are the ones who seem to perform best physically at great heights. In both the AMREE subjects[8] and the members of a Japanese expedition to Kanchenjunga, the world's third highest mountain (8565 m),[6] there was an association between high hypoxic ventilatory response and better physical performance. Although the subjects of Operation Everest II who were capable of a higher maximal oxygen consumption had a substantially improved performance on several parts of the Selective Reminding Test, no correlation of maximal oxygen uptake with hypoxic ventilatory response was found. Also, measurements of maximal oxygen uptake in a short, exhaustive test may not predict performance during a high-altitude climb. This improved physical capability is probably conferred by the higher hypoxic ventilatory response, which yields higher oxygenation of arterial blood. Thus, the high hypoxic ventilatory response may enhance the delivery of oxygen to exercising muscle while at the same time the resulting hypocapnic vasoconstriction of the cerebral vessels may reduce the transport of oxygen to the central nervous system.

These studies show that some persons who climb to extremely high altitudes have transient neurobehavioral impairment afterward. Especially with more prolonged and repeated exposure, there is the possibility

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that long-lasting impairment may occur without the loss of consciousness or other obvious alteration of function at high altitude. Higher levels of resting arterial oxygenation consequent to a brisk ventilatory response to hypoxia were associated with poorer neurobehavioral outcomes. This unexpected finding may be explained by decreases in the cerebral blood flow and the delivery of oxygen to the brain due to hypocapnia at rest or during exercise or by moments of severe arterial hypoxemia associated with greater periodicity of breathing during sleep in persons with a higher hypoxic ventilatory response.

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