Barometric pressures at extreme altitudes on Mt. Everest: physiological significance

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WEST, JOHN B., SUKHAMAY LAHIRI, KARL H. MARET, RICHARD M. PETERS, JR., AND CHRISTOPHER J. PIZZO. *Barometric pressures at extreme altitudes on Mt. Everest: physiological significance.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 54(5): 1188–1194, 1983.—Barometric pressures were measured on Mt. Everest from altitudes of 5,400 (base camp) to 8,848 m (summit) during the American Medical Research Expedition to Everest. Measurements at 5,400 m were made with a mercury barometer, and above this most of the pressures were obtained with an accurate crystal-sensor barometer. The mean daily pressures were 400.4 ± 2.7 (SD) Torr (n = 35) at 5,400 m, 351.0 ± 1.0 Torr (n = 16) at 6,300 m, 283.6 ± 1.5 Torr (n = 6) at 8,050 m, and 253.0 Torr (n = 1) at 8,848 m. All these pressures are considerably higher than those predicted from the ICAO Standard Atmosphere. The chief reason is that pressures at altitudes between 2 and 16 km are latitude dependent, being higher near the equator because of the large mass of cold air in the stratosphere of that region. Data from weather balloons show that the pressure at the altitude of the summit of Mt. Everest varies considerably with season, being about 11.5 Torr higher in midsummer than in midwinter. Although the mountain has been climbed without supplementary O_2, the very low O_2 partial pressure at the summit means that it is at the limit of man's tolerance, and even day-by-day variations in barometric pressure apparently affect maximal O_2 uptake.

hypoxia; work capacity; oxygen partial pressure; exercise tolerance

IT HAS BEEN RECOGNIZED for many years that the hypoxia caused by the low barometric pressures of extreme altitudes may severely limit human performance. As long ago as 1909 many physiologists were astonished when the Duke of the Abruzzi reached the extraordinary altitude of 7,500 m in the Karakoram Mountains without supplementary O_2 (6). After this ascent, Douglas and his co-workers (5) made some calculations from the reported barometric pressure of 312 Torr and concluded that adequate oxygenation of the arterial blood would be impossible under these conditions without active secretion of O_2. However, in 1924, Norton (14), breathing ambient air, reached an altitude of 8,500 m on Mt. Everest, although his dramatic account leaves little doubt that he was very near his limit of tolerance. Nevertheless, Messner and Habeler achieved the ultimate in 1978, reaching the summit of Mt. Everest (alt 8,848 m) without supplementary O_2. Their accounts (9, 13) clearly indicate the slim margin of reserve at these extreme altitudes.

Stimulated by these remarkable climbs, we carried out a theoretical analysis of pulmonary gas exchange at extreme altitudes up to the summit of Mt. Everest (19). This study suggested that the maximal O_2 uptake ($\dot{V}O_{2\,max}$) on the summit was only slightly above the basal O_2 requirements of the body. Another conclusion was that the predicted $\dot{V}O_{2\,max}$ was exquisitely sensitive to small variations in barometric pressure. These predictions emphasized the need for more data on barometric pressure above altitudes of 8,000 m where direct measurements on mountains have not yet been reported. In another theoretical study, Dejours (4) reached similar conclusions.

A further reason for our interest in barometric pressure is that it has been known for many years that the relationship between barometric pressure and altitude on many mountains is different from that predicted from the standard altitude-pressure tables (12). Thus the barometric pressure for the altitude of the summit of Mt. Everest (8,848 m) predicted from the standard table is 236 Torr. Our theoretical analysis (19) clearly showed that if the pressure were as low as this it would certainly be impossible to reach the summit without supplementary O_2. Pugh (16) pointed out that the altitude-pressure relationship on many mountains more closely follows the semiempirical formula given by Zuntz et al. (20) rather than the standard atmosphere, and many physiologists have used the Zuntz curve (7, 10), though others have elected to use the pressures predicted by the standard atmosphere (11).

One of the principal objectives of the American Medical Research Expedition to Everest, which took place in the fall of 1981, was to study human physiology at altitudes over 8,000 m. Seven readings of barometric pressure were obtained above 8,000 m, including one measurement on the summit of Mt. Everest itself. In this paper we report these data and discuss their physiological significance.

METHODS

Barometric Pressure Measurements

Base Camp. Pressures were measured using a Fortin mercury barometer specially shortened for our expedi-

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tion so that the low pressures fell on scale (Meriam Instruments, Cleveland, OH). The barometer was filled with mercury at the Base Camp (alt 5,400 m) and mounted on the wall of the rigid Base Camp laboratory hut. The laboratory was kept warm with a propane heater that was thermostatically controlled so that most of the time the temperature was 10–16°C. However, in the last 4 days of the expedition we ran out of propane and the temperature in the laboratory fell to as low as −8°C. The barometer was read each morning, and the readings were subsequently corrected to 0°C and 45° latitude.

Measurements above Base Camp. These measurements were made using a small portable barometer specially designed and constructed for the expedition. The pressure transducer was a crystal with one side exposed to a vacuum and the other to the air pressure. The two faces of the crystal were silvered, and changes in atmospheric pressure altered the shape of the crystal and thus the electrical capacity (Airesearch, Torrance, CA). The transducer had a digital output that was fed to a liquid crystal display. The box also included a thermistor thermometer, and either pressure or temperature could be digitally displayed by means of a selector switch.

The pressure transducer had a high intrinsic accuracy of ±0.1% full scale and was rated to an altitude of 30,000 m. The output was essentially independent of temperature over the range of −54 to +85°C. We directly calibrated the crystal-sensor barometer against the mercury barometer for 6 days at Base Camp, making measurements each day. The mean difference in the readings was less than 0.5 Torr, with a maximal disparity of 0.6 Torr. We have therefore not corrected the readings of the crystal-sensor barometer.

Measurements of barometric pressure at Camp 2 were also made with an aneroid barometer of high accuracy (Revue Thommen, Switzerland) when the crystal-sensor barometer was at higher camps. In all, 16 measurements of barometric pressure were made at Camp 2 (alt 6,300 m), 6 with the crystal-sensor barometer (Oct 3 through 9) and 10 with the aneroid instrument (Sep 28 and Oct 10 through 19). The absolute value of these readings is of little significance, because the altitude of the camp was not accurately known. However, the readings give information about the day-by-day variations of barometric pressure. Six daily readings were made with the crystal-sensor barometer at Camp 5 (alt 8,050 m). The dates were October 12, 13, 16, and 23 through 25. We can be confident about this altitude, because it was estimated by several climbers to be about 200 feet (61 m) above the South Col of Everest, which has been accurately surveyed and has an altitude of 7,986 m (18). One measurement was made with the crystal-sensor barometer on the Everest summit at 12:30 P.M. on October 24 by Pizzo. The reading (253.0 Torr) was immediately recorded onto a small dictating tape recorder.

Weather Balloon Data

Weather balloons are released twice daily at a weather station in New Delhi, India (28°35′N, 77°12′E), and these provide the altitudes (surfaces) for barometric pressures of 200, 300, and 500 mbar (3). The pressures for an altitude of 8,848 m were obtained by interpolation using the 200-, 300-, and 500-mbar surfaces. The relationship between elevation and the log of pressure is very nearly linear. This method gives slightly higher pressures (1–2 Torr) than obtained by interpolating from the 300- and 500-mbar altitudes alone (19) because of the slight nonlinearity of log pressure against altitude. The mean pressures and standard deviations were calculated for each month of the year for a 15-yr period. Data were also obtained for October 24, 1981, which was the day of our measurement of barometric pressure on the Everest summit, and for May 8, 1978, when the mountain was first climbed without supplementary O_2 (9, 13).

RESULTS

Barometric Pressure Measurements

Base Camp (alt 5,400 m). Barometric pressures measured with the mercury barometer are shown in Table 1 and Fig. 1. Note that the mean value for the period from September 19 through October 26 was 400.4 Torr with a standard deviation of 2.7 Torr. No measurements were made on September 17 through 19, because all the observers were above Base Camp. Barometric pressures were also measured at Base Camp with the crystal-sensor barometer before the mercury barometer arrived. For the period August 30 through September 18 the mean value was 401.3 ± 0.6 (SD) Torr.

Figure 1 shows that there was a trend for barometric pressure to fall slightly during the period September 19 through October 26. The slope of the regression line is 0.19 Torr/day (n = 35; r = −0.78; P < 0.01). This is consistent with the known fall in mean barometric pressure that occurs from the summer to the winter months (see Fig. 3).

The altitude of Base Camp was determined from a map based on previous trigonometric surveys (18). The site of the camp on the map can be determined with considerable confidence, because it was situated very near the bottom of the Khumbu ice fall at the head of the Khumbu valley. The valley is fairly flat at this point, and the contour lines are widely separated.

Camp 2 (alt 6,300 m). Barometric pressures here were measured with the crystal-sensor barometer from October 3 through 10, and on September 28 and October 11 through 19 they were measured with the aneroid barometer. Table 1 shows that the mean pressure was 351.0 ± 1.0 (SD) Torr. Note that these data are not very useful for determining the barometric pressure-altitude relationship because of uncertainty about the altitude of this camp.

Camp 5 (alt 8,050 m) and summit (alt 8,848 m). All these pressures were determined with the crystal-sensor barometer. As indicated above, this was checked against the mercury barometer at Base Camp during the period September 19 through 25, and close agreement was demonstrated. The mean barometric pressure at Camp 5 was 283.6 ± 1.5 (SD) Torr. The one measurement of barometric pressure on the summit was obtained on October 24, the value being 253.0 Torr.

TABLE 1. *Barometric pressures on Mt. Everest*

Date	Base Camp, 5,400 m		Camp II, 6,300 m		Camp V, 8,050 m		Summit, 8,848 m	
	PB, Torr	T_a, °C	PB, Torr	T_a, °C	PB, Torr	T_a, °C	PB, Torr	T_a, °C
Sep								
19	400.2	15						
20	401.6	13						
21	402.0	13						
22	402.5	15						
23	402.8	1						
24	402.6	12						
25	403.3	16						
26	404.3	17						
27	404.0	13						
28	402.0	15	352.0	13				
29	400.6	13						
30	402.0	12						
Oct								
1	401.4	13						
2	401.1	14						
3	402.3	14	352.3	5				
4	401.4	15	350.8	−5				
5	400.4	16	352.2	16				
6	401.6	13	351.6	14				
7	401.4	15	352.4	18				
8	401.3	16						
9	402.1	3	351.8	16				
10	400.6	11	350.2	19				
11	400.7	15	350.2	20				
12	401.6	12	350.9	13	282.1	−18		
13	402.7	8			281.5			
14	402.2	15	348.8	14				
15	395.4	15	350.5	10				
16	395.1	21	350.5	12	283.9			
17			350.3	9				
18			349.9	14				
19			351.0	15				
20	396.8	25						
21	396.7	12						
22	396.9	11						
23	395.8	−2			285.1			
24	396.7	−8			284.5		253.0	−9
25	395.9	−8			284.7	−12		
26	396.2	4						
Mean ± SD	400.4±2.7		351.0±1.0		283.6±1.5		253.0	
n	35		16		6		1	

PB, barometric pressure; T_a, ambient temperature; *n*, no. of observations.

The altitude of the summit is accurately known because of trigonometric surveys both from the south and the north. We can also be confident of the altitude of Camp 5 for the reasons discussed above. Two measurements of temperature were recorded at Camp 5. These were −18°C on October 12 at 6:30 P.M. and −12°C on October 25 at 10 A.M. The temperature on the summit at 12:30 P.M. on October 24, a clear sunny day, was −9°C, which is exceptionally warm for that altitude. The average temperature for an altitude of 8,848 m at this latitude at this time of the year as determined from weather balloons is approximately −25°C, though this may be altered near a mountain surface. It should be noted that the thermometer-barometer was kept in Pizzo's red backpack until he reached the summit and then held in the hand for the measurement. It is therefore possible that the reading was elevated by direct radiation from the sun.

Barometric Pressure-Altitude Relationship

Figure 2 shows barometric pressure on a semilogarithmic scale plotted against altitude. The three data points on the solid line indicate the means of the barometric pressures at altitudes that were known with a high degree of confidence. The pressures measured at Camp 2 are omitted because of uncertainty about that altitude, though they lie very close to the line. Figure 2 also shows the barometric pressure-altitude relationship for the ICAO Standard Atmosphere. Note that the actual measured values are substantially above those predicted from the model atmosphere. For example, at the Everest

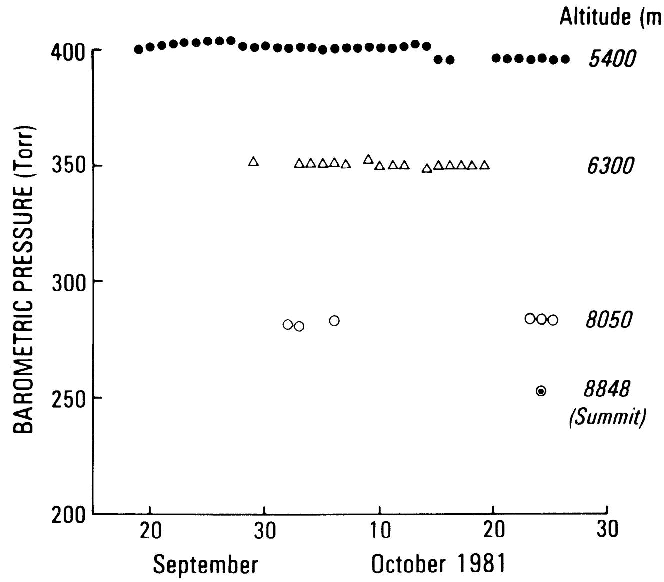

FIG. 1. Barometric pressures on Mt. Everest. Pressures at Base Camp were measured with a mercury barometer. Pressures at higher camps were measured with a crystal-sensor barometer, except for some measurements at Camp II, which were made with an aneroid barometer.

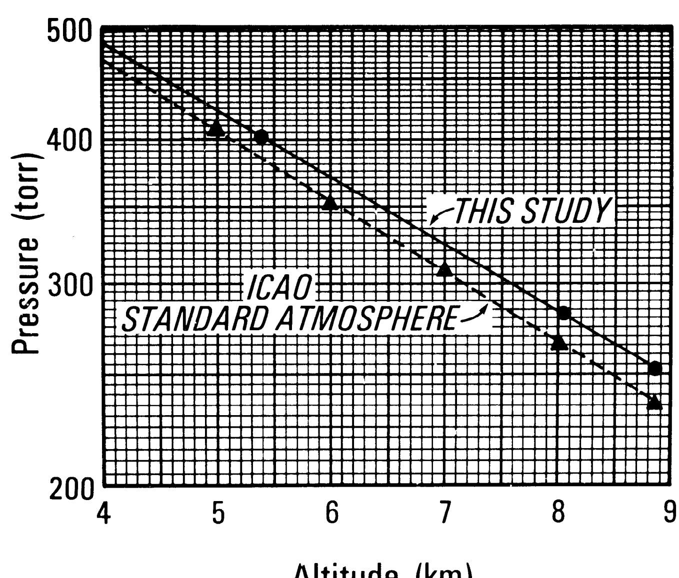

FIG. 2. *Solid line*, barometric pressure-altitude relationship on Mt. Everest during Sep–Oct 1981; 3 data points are for altitudes that are accurately known. *Broken line*, relationship for ICAO Standard Atmosphere (12).

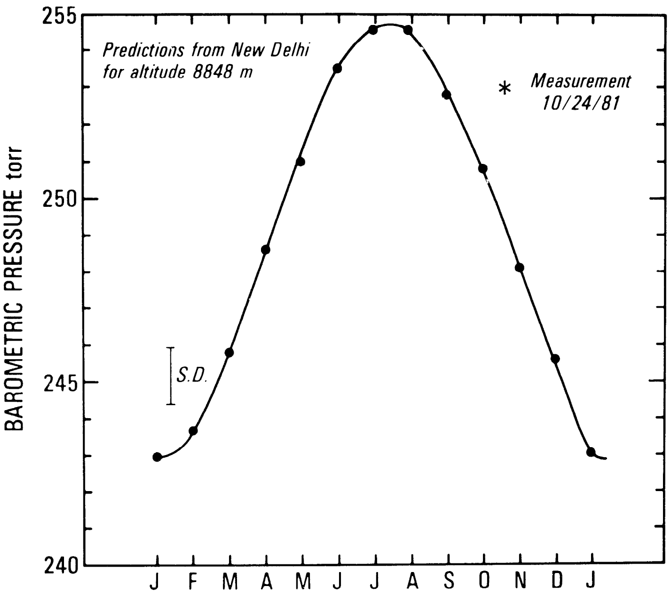

FIG. 3. Mean monthly pressures for 8,848-m altitude as obtained from weather balloons released from New Delhi, India. Note increase during summer months. Mean monthly standard deviation is also shown. Barometric pressure measured on Everest summit on Oct 24 was unusually high.

summit, the measured value (253.0 Torr) was 17 Torr higher than that indicated by the model atmosphere.

Weather Balloon Data for Altitude 8,848 m near New Delhi, India

Figure 3 shows data obtained from weather balloons released twice daily from a weather station in New Delhi, India. Although this site is 1,000 km west of Mt. Everest, it is the nearest station with the same approximate latitude. As discussed below, the barometric pressure-altitude relationship is strongly latitude dependent.

Figure 3 shows the mean monthly pressures determined from data gathered over a period of 15 yr. Note that the mean pressures were lowest in the winter months of January and February (243.0 and 243.7 Torr, respectively) and highest in the summer months of July and August (254.5 Torr for both months). The monthly standard deviation showed a range of 0.65 Torr (July) to 1.66 Torr (December). The daily standard deviation was as low as 1.54 in the summer and as high as 2.92 in the winter. The standard deviation shown on Fig. 3 is the mean of the monthly standard deviations for the 12 mo of the year.

The single measurement of barometric pressure (253.0 Torr) made on October 24 was 4.3 Torr higher than that predicted from the data shown in Fig. 3. This is 2.0 times the daily standard deviation of barometric pressure for the month of October.

Weather maps were also obtained for the Northern Hemisphere for the day that the measurement of summit pressure was made. The maps were available for October 24, 1981 at 12 noon GMT (5:40 P.M. Nepalese time), some 5 h after Pizzo took the reading. They showed that the heights of the 500, 300, and 200 mbar surfaces near New Delhi were 5,860, 9,650, and 12,380 m, respectively. Using the near-linear relationship between log pressure and altitude, this gives a pressure at 8,848 m altitude of 252 Torr, which is in close agreement with the measured value.

Maps were also obtained for May 8, 1978, the day on which Messner and Habeler first reached the summit without supplementary O_2. Using the same procedure described above, the barometric pressure for an altitude of 8,848 m was 251 Torr.

DISCUSSION

Comparison with Measurements of Others

Our measurements of barometric pressure are in general agreement with measurements by other workers at lower altitudes on Mt. Everest and on other nearby Himalayan mountains (2, 16, 17). In 1957, Pugh made some calculations based on a measurement of barometric pressure at an altitude of approximately 7,315 m on Mt. Everest during the 1953 British Expedition. The pressure was 308 Torr, and he assumed a mean temperature of −26°C between that altitude and the summit based on temperature measurements up to an altitude of 8,500 m. His prediction for the pressure on the summit was 250 Torr, which was remarkably accurate in the light of present-day knowledge. However, in the same article he also predicted from the measurements of Greene (8) in 1934 that the summit pressure was as high as 269 Torr at that time. This is clearly an overestimate. Incidentally, 269 Torr is the summit pressure predicted from the Zuntz curve (20).

During the Himalayan Scientific and Mountaineering Expedition of 1960–1961, barometric pressure measurements with an aneroid barometer were made as high as 7,440 m on the Makalu Col. The pressure there was 300 Torr. From these and other data we predicted a barometric pressure on the summit of Mt. Everest of 250 Torr before the present expedition (19). A series of measurements was made at the Everest Base Camp by Cerretelli (2) in 1973, and he reported a mean pressure of about 390 Torr. The altitude of the camp was given as 5,350 m. Although these observations were made in the spring before the monsoon season, the values are surprisingly low when compared with our measurements as shown in Table 1.

It should be emphasized that many of the measurements that have previously been reported are of limited value in accurately determining the barometric pressure-altitude relationship. For these data to be useful, we need to know the altitude with precision, and usually this can be done only at easily identified sites, such as the top of the Khumbu valley, the South Col, Makalu Col, or a summit. Measurements reported from camps in the Western Cwm of Mt. Everest, for example, are difficult to interpret because of uncertainty about the altitude.

Barometric Pressure-Altitude Relationship and Latitude

It has been recognized for many years that the barometric pressures at high altitudes on mountains in the equatorial or temperate zones are often considerably higher than those predicted from the ICAO Standard

Atmosphere. For example, Pugh (16) showed that his measurements of barometric pressure made on Mt. Everest fell well above the predictions from the model atmosphere, whereas they agreed fairly well with the formula proposed by Zuntz et al. (20). Other investigators (7, 10) have also shown that their pressure measurements fell close to the Zuntz curve.

The Standard Atmosphere is constructed from a model that assumes a constant lapse rate of temperature of 6.5°C/km up to an altitude of 11 km. It should be emphasized that this model atmosphere was never meant to be used to predict the actual barometric pressure at a particular location. Rather it was developed as a model of more-or-less average conditions within the troposphere with full recognition that there would be local variations caused by latitude and other factors. Nevertheless the Standard Atmosphere has assumed some importance in respiratory physiology, because it is universally used as the standard for altimeter calibrations. It is also employed for determining altitude equivalents in low-pressure chamber experiments and thus for predicting the physiological effects of altitude exposure.

However, barometric pressure at any given altitude varies considerably with latitude as shown in Fig. 4. Note that the barometric pressures at the Earth's surface and also at an altitude of 24 km are essentially independent of latitude. However, in the altitude range of about 2–16 km, there is a pronounced bulge in barometric pressure near the equator both in winter and summer. Since the latitude of Mt. Everest is 28°N, the pressure at its summit (8,848 m) is considerably higher than would be the case

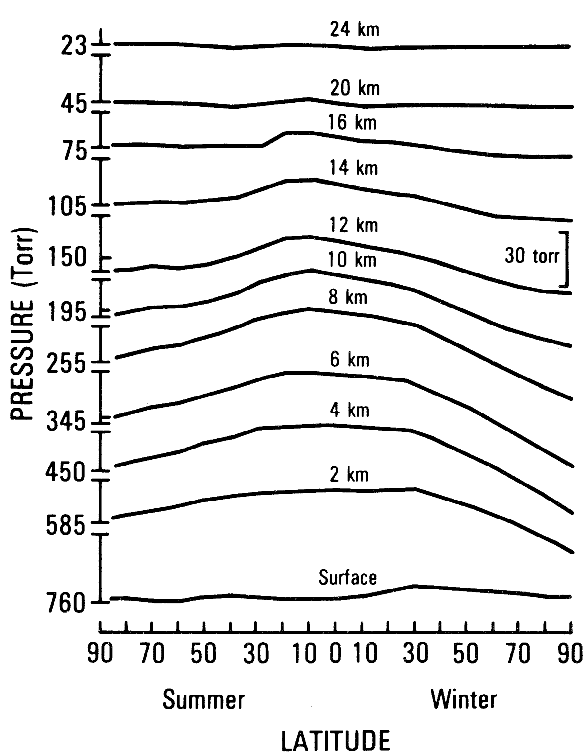

FIG. 4. Increases of barometric pressure near equator at various altitudes in both summer and winter. *Vertical scale* shows pressure increasingly upward according to scale on *right*. Numbers on *left* show barometric pressures at the poles for various altitudes. Modified from Brunt (1).

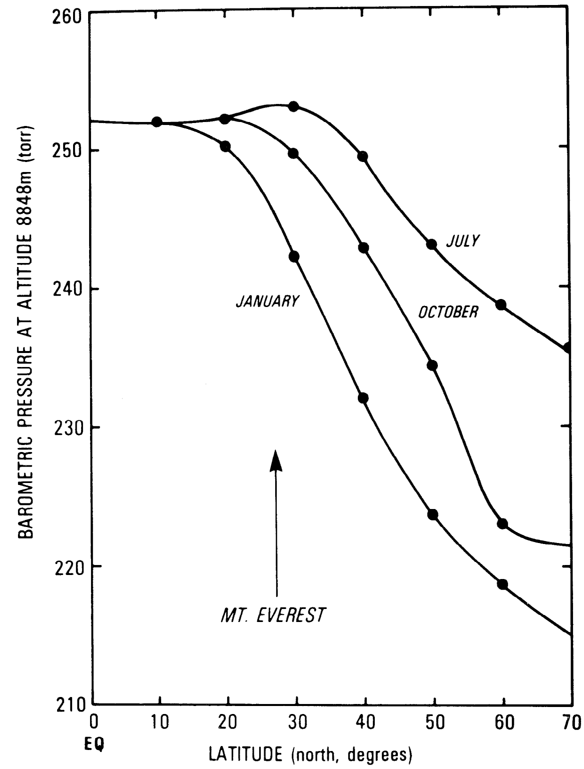

FIG. 5. Barometric pressure at altitude of Mt. Everest plotted vs. latitude in Northern Hemisphere for midsummer, midwinter, and preferred month for climbing in postmonsoon period (Oct).

for a hypothetical mountain of the same height near one of the poles.

The way in which pressure varies with latitude according to the season of the year is shown in Fig. 5. The data are for the Northern Hemisphere, and the pressures for the months of January (midwinter), July (midsummer), and October (preferred month for climbing in the postmonsoon period) are compared. The profile for the month of May, which is the usual month for reaching the summit in the premonsoon season, is almost the same as that for October. The data are the means from all longitudes (15). The figure clearly shows the marked effect of latitude on barometric pressure. It is interesting that in midsummer the pressure reaches a maximum near the latitude of Mt. Everest (28°35′N).

The cause of the bulge in barometric pressure near the equator is a very large mass of very cold air in the stratosphere above the equator (1). In fact, paradoxically, the coldest air in the atmosphere is above the equator. This is brought about by a combination of complex radiation and convective phenomena. Another corollary of the same phenomenon is that the height of the tropopause, i.e., the junction between the troposphere, where all the weather events take place, and the stratosphere, where the temperature of the air is essentially independent of altitude, is much higher near the equator than near the poles. These latitude-dependent variations of pressure are of great physiological significance for anyone attempting to climb Mt. Everest without supplementary O_2, since they result in a barometric pressure on the Everest summit some 17 Torr higher (for our measurements) than that predicted from the model atmosphere.

Data from Weather Balloons Released from New Delhi, India

The data shown in Fig. 3, based on information from weather balloons released from New Delhi, are of interest. It is clear that the variation of barometric pressure with season during the year is considerable and that a climber planning an ascent of Mt. Everest without supplementary O_2 in the winter would be at a considerable disadvantage compared with the summer. As an example, our previous theoretical analysis (19) showed that a fall of 4 Torr in barometric pressure from 250 to 246 Torr would reduce the predicted $\dot{V}O_{2\,max}$ of a climber on the summit by about 10%. The pressure variations as great as 11.5 Torr shown in Fig. 3 are therefore of considerable physiological significance.

It is notable that our single measurement of barometric pressure on the Everest summit, made on October 24, was two daily standard deviations above the mean monthly pressure for that time of the year; thus the day chosen by Pizzo and Hackett for their summit ascent was exceptional. As Table 1 shows, the temperature on the summit at 12:30 P.M. was −9°C, extraordinarily high for that altitude. The average temperature predicted at that altitude and latitude for that time of the year is about −25°C. The combination of unusually warm weather up to an altitude of 9,000 m with a high pressure at that altitude is a typical pattern for a high-pressure system.

Occasionally it has been suggested that the high winds associated with the mountains may cause local variations in barometric pressure. However, calculations from Bernoulli's equation show that the resulting change in pressure is small, certainly less than 1 Torr. Also variations in gravity over the Earth's surface have a negligible effect.

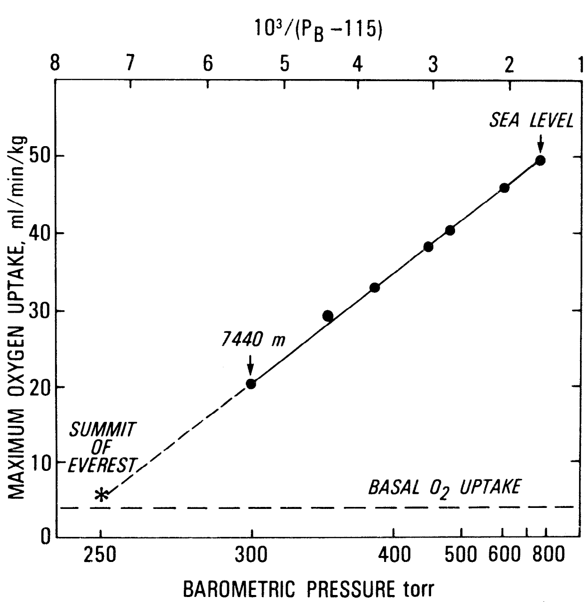

FIG. 6. Maximal O_2 uptake ($\dot{V}O_{2\,max}$) of acclimatized subjects plotted vs. barometric pressure using the data of Pugh et al. (17). Barometric pressure axis has been transformed according to the expression at top of graph to give a linear relationship so that extrapolation to 250-Torr pressure can be made. Note that $\dot{V}O_{2\,max}$ predicted for Everest summit is very close to basal O_2 requirements. From West and Wagner (19).

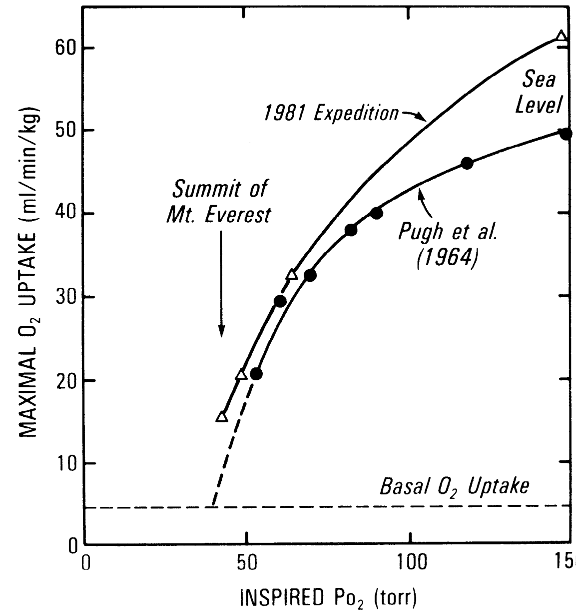

FIG. 7. Same data as Fig. 6 but plotted with inspired O_2 partial pressure (P_{O_2}) on *horizontal axis*, which is now linear. In addition, data on maximal O_2 uptake ($\dot{V}O_{2\,max}$) obtained on present expedition are shown. Again, sensitivity of $\dot{V}O_{2\,max}$ to inspired P_{O_2}, and therefore barometric pressure, is seen.

Physiological Significance

There is evidence that small variations in barometric pressure are of critical importance in determining work capacity at extreme altitudes like the summit of Mt. Everest. For example, consider the data obtained during the Himalayan Scientific and Mountaineering Expedition of 1960–1961 (17) where measurements of $\dot{V}O_{2\,max}$ were obtained up to an altitude of 7,440 m (300 Torr). $\dot{V}O_{2\,max}$ declined by only 19% between sea level and an altitude of 4,650 m (a fall of 310 Torr in pressure), whereas $\dot{V}O_{2\,max}$ fell by 30% from 6,400 m to 7,440 m (pressure decrease of only 40 Torr). Figure 6 shows data that were obtained in acclimatized subjects. In this plot the barometric pressure axis was transformed to give a linear relationship between $\dot{V}O_{2\,max}$ and barometric pressure so that the line could be extrapolated to the barometric pressure at the Everest summit. Note that the predicted $\dot{V}O_{2\,max}$ at a barometric pressure of 250 Torr is apparently very close to the basal O_2 requirements.

In Fig. 7 the same data are plotted, but this time with inspired O_2 partial pressure (P_{O_2}) on the horizontal axis, which is now linear. The great sensitivity of predicted $\dot{V}O_{2\,max}$ to small changes in barometric pressure near the summit can be appreciated. In addition, Fig. 7 shows data on $\dot{V}O_{2\,max}$ measured at different values of inspired P_{O_2} on the present expedition. It can be seen that although the curve is displaced to the left, the sensitivity to inspired P_{O_2}, and therefore barometric pressure, is confirmed.

All these data strongly suggest that it would be impossible for a climber to reach the summit of Mt. Everest without supplementary O_2 if the barometric pressure there were as low as the Standard Atmosphere predicted. Thus it is remarkable that the latitude-dependent increase in barometric pressure shown in Fig. 4 makes it just possible. It remains for someone to elucidate the evolutionary processes responsible for man being just able to reach the highest point on Earth while breathing ambient air.

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