J. Physiol. (1957) 135, 590–610

RESTING VENTILATION AND ALVEOLAR AIR ON MOUNT EVEREST: WITH REMARKS ON THE RELATION OF BAROMETRIC PRESSURE TO ALTITUDE IN MOUNTAINS

By L. G. C. E. PUGH

From the Division of Human Physiology, National Institute for Medical Research, Hampstead, London, N.W. 3

(*Received* 27 *September* 1956)

The physiological changes associated with acclimatization to high altitude have been thoroughly investigated up to 15,000 ft., but at greater heights the data become increasingly scarce. The International Physiological Expedition to Chile in 1935 made observations on themselves and the local miners at 17,500 ft.; and short visits were made to 20,100 ft. (Dill, Christensen & Edwards, 1936). Houston & Riley (1947) studied four subjects over a 4-week period in a decompression chamber at pressures which were reduced by slow stages to the equivalent of an altitude of 20,000 ft. Above that there are only the alveolar air samples taken by Greene (1934) and Warren (1939) on pre-war expeditions to Mount Everest. Some earlier data by Somervell on the 1924 expedition are not acceptable because the samples were stored in rubber bags. Both Greene and Warren stored their samples in glass ampoules. They brought back between them eleven samples, ten of which were taken at altitudes between 20,000 and 22,800 ft., and a single sample taken at 25,700 ft.

The observations reported in this paper were made on the British Himalayan expeditions to Mount Cho Oyu (26,570 ft.) and Mount Everest (29,002 ft.) in 1952 and 1953. Their purpose was to supplement and extend existing physiological data on persons acclimatized to very high altitudes. Alveolar air samples were obtained from members of both parties at altitudes ranging from 15,000 to 24,000 ft., and resting ventilation was followed in a single subject at altitudes up to 21,200 ft. Data on the effect of breathing supplementary oxygen on the alveolar gases in resting subjects are also presented. The primary purpose of these observations was to look for evidence of slow loss of acclimatization in persons using oxygen over prolonged periods.

Barometric pressures on Everest were found to correspond more closely with pressures calculated from a formula proposed by Zuntz, Loewy, Müller & Caspari (1906) which was used by Fitzgerald (1913) in presenting the results of a study of alveolar air made on the Pike's Peak Expedition (Douglas, Haldane, Henderson & Schneider, 1913), than with the internationally adopted altimeter calibration formula used in aviation and in decompression chamber studies. The matter is dealt with in some detail in this paper because it would appear that the pressures used to simulate altitudes over 15,000 ft. in the decompression chamber are considerably lower than the corresponding pressures usually observed on mountains; and furthermore it seems likely that the barometric pressure near the summit of Mount Everest, when attempts have been made to climb it, has been considerably higher than would be inferred from the altimeter scale.

METHODS

Barometric pressure and altitude. The 1952 expedition was equipped with surveyor's aneroids, which proved unreliable above 16,000 ft. A member of the expedition, T.D.B., however, had with him an aircraft aneroid, which seemed satisfactory; so in 1953 two instruments of this type were included in the physiological equipment. These were supplied by Messrs Kelvin Hughes who calibrated them specially, before and after the expedition, over an appropriate range of pressures and temperatures. Readings taken on both instruments at different stages of the expedition agreed within 2 millibars. In calculating the results of physiological studies made on the 1952 expedition, barometric pressures at altitudes over 16,000 ft. have been taken from observations made at corresponding altitudes on the Mount Everest expedition. The justification for these assumed barometric pressures was the fact that both expeditions operated in the same territorial region and at the same time of year, readings at lower altitudes showed good agreement, and at 18,000 ft. and over on Mount Everest variations in barometric pressure due to the weather were small.

Altitudes on the Mount Cho Oyu expedition were taken from the Royal Geographical Society's map 'Mount Everest and Environs', compiled from the Mount Everest surveys of 1921 and 1924, and the Nepal survey of 1924–27. On the 1953 Mount Everest expedition the height of the summit was taken to be 29,002 ft. The most recent survey (Gulatee, 1954) places it at 29,028 ft. The heights of Thyangboche (13,200 ft.) and of the South Col (25,850 ft.) relative to Everest were established by geometric methods, the former by Evans on the 1953 expedition, the latter by the 1921 Everest reconnaissance party. The heights of the intermediate camps, which are those given by Hunt (1953) in the official account of the expedition, although not measured geometrically, are considered to be accurate to within about 200 ft. They were based on the combined evidence of photographs, climbing times, and aneroid differences as well as the estimates of the two Swiss expeditions in 1952.

The barometric pressures observed at various heights on Mount Everest have been compared with the internationally adopted altimeter calibration curve, and with the curve used by Fitzgerald (1913) based on the formula proposed by Zuntz *et al.* (1906). The formulae from which they are calculated are as follows:

(1) The internationally adopted altimeter calibration formula, which assumes a standard atmosphere having a temperature of +15° C and pressure of 760 mm Hg at sea level, and a lapse rate of 0·0019812° C/ft. The formula appears in various forms in different reference books. Haldane & Priestley (1935*b*) in 'Respiration' give the form

$$\frac{P_0}{P}=\left(\frac{288}{288-1{\cdot}98H}\right)^{5{\cdot}256},$$

where P_0 and P are the pressures in mm Hg at sea level and at height H thousand feet.

Boothby's *Handbook of Respiratory Data in Aviation* (1944) gives it as

$$Z = 221{\cdot}15\, T_{\mathrm{ms}} \log \frac{760}{P_B},$$

$$T_{\mathrm{ms}}\ (\text{degrees absolute}) = \frac{aZ}{2{\cdot}303 \log \dfrac{288}{288 - aZ}},$$

where Z is the altitude in feet, a is the standard lapse rate (*v. supra*) and P_B is the barometric pressure in mm Hg at height Z ft. Where an accuracy of 1 mm Hg is acceptable, the simpler arithmetic mean temperature can be used instead of the logarithmic mean, T_{ms}, to calculate pressures corresponding to altitude up to 30,000 ft.

(2) Zuntz's formula (Zuntz *et al.* 1906) is

$$\log b = \log B - \frac{h}{72\,(256{\cdot}4 + t)},$$

where B is the barometric pressure at the lower level in mm Hg, b is the barometric pressure at the upper level in mm Hg, h is the difference in height in metres, t is the mean temperature (° C) of a column of air of height h. Fitzgerald (1913) showed that barometric pressures calculated from this formula corresponded closely with pressures observed in mountains when a sea-level pressure of 760 mm Hg and a mean temperature of $+15°$ C were assumed.

Resting ventilation. Observations were made on G.P. at various stages of both expeditions. Ventilation was measured in the morning before rising, half to one hour after drinking a mugful of tea containing about one ounce of sugar. The apparatus was put ready the night before to minimize the amount of movement before the experiment. In 1952 a Max Planck Institute respiration meter (Orsini & Passmore, 1951) was employed, including the Perspex valve unit, corrugated tubing and nose-clip supplied with the instrument. The calibration of the instrument was checked before and after the expedition. In 1953, expired air was collected directly into a light-weight 80 l. bag, with manual control of the neck, and its volume was determined from measurements of the pressure and temperature of the gas, as described in a previous communication (Pugh, 1953). Comparable results have been obtained in this subject by both methods up to minute volumes of 30 l./min (Pugh, 1953).

Alveolar air. On the 1952 expedition the first samples of alveolar air were taken on the fourth day after arrival at 11,600 ft. after a three-week approach march at intermediate altitudes, mostly between 6000 and 10,000 ft. The first observation at 20,000 ft. was made on the third day after a two-day ascent from a camp at 15,500 ft., where the party had been resting for a week after a month spent at altitudes between 18,000 and 21,000 ft. In 1953 observations were begun a month after arriving in the Everest region, after an approach march similar to the one in 1952. Ward and Wylie who gave the first samples, on 30 April, had been ferrying stores between base camp (18,000 ft.) and the Western Cwm (20,000–22,000 ft.), for three weeks, and had twice been to nearly 20,000 ft. before that. A series of samples were taken by G.P. on himself at base camp, 18,000 ft., on 8 May (27th day after arrival) during the control period of the oxygen experiment described below, and further samples were taken at Camp III (20,500 ft.), during an 11-day stay (date of arrival 11 May) and at Camp IV (21,200 ft.) during a seven-day stay (date of arrival 25 May). Samples on other subjects at these camps were taken after 10 May, when the party had moved into the Cwm and were operating between 20,500 and 22,500 ft. and sometimes above. Ward took samples at Camp VII (24,000 ft.), on the day after ascending from Camp V (22,500 ft.) without using oxygen apparatus.

The samples were end-expiratory samples (Haldane & Priestley, 1935*a*) taken with a 3 ft., 1 in. internal diameter hose-pipe. They were collected in 50 ml. evacuated glass ampoules by a method similar to that used by Greene on the 1933 Everest expedition (Greene, 1934). The ampoules were sealed immediately over a butane-gas flame and were brought back to England for analysis. The analyses were done on a Micro-Scholander Gas Analyser (Scholander, 1947). Care was taken to ensure that the subjects were adequately trained in the method, and they were watched to see that the samples were given correctly without interruption of breathing rhythm or abnormal inspiration before delivering the sample. All samples taken during the day-time were delivered in the sitting position. Samples taken in the evening after 8.0 p.m. were taken from subjects lying in the supine position in their sleeping bags with the head and shoulders supported.

Experiments with oxygen. The effect of breathing supplementary oxygen from an open circuit apparatus at a flow rate of 2 l. of oxygen /min (s.t.p.) was studied at base camp (18,000 ft.) 4 weeks after arrival there. The observations were made during a 3 hr control period on air, and a 3 hr period on oxygen. The author acted as subject, delivering samples directly into a 20 ml. glass syringe and analysing them immediately for CO_2 on the Micro-Scholander apparatus. The subject was well acclimatized, and did not notice any obvious effect on breathing oxygen.

Some observations on the short term or immediate effect of breathing oxygen on the alveolar pCO_2 were made on 21, 22 and 23 May, at Camp III (20,500 ft.). The subject had been at Camp III from 11 to 17 May; he had been down to base camp (18,000 ft.) on 18 May, returning the following day. The samples were taken before and during a 10 min period on oxygen. In the first experiment oxygen was inhaled from a closed circuit apparatus; in the other experiments a 200 l. bag containing 100% oxygen was used.

Experiments on the long-term effect of oxygen on alveolar pCO_2 were done on both the 1952 and 1953 expeditions at altitudes between 20,000 and 21,200 ft. Alveolar samples were taken before, during and after periods of breathing oxygen at night for sleeping. Oxygen was supplied to the subjects at the rate of either 1 or 2 l./min using a light-weight mask and reservoir bag, similar to the emergency sets used in civil aviation. The samples were taken with the subjects lying in their sleeping bags, beginning about 1 hr after supper. The procedure consisted of raising the mask with one hand at the end of inspiration and with the other applying the end of the hose-pipe to the mouth. With practice this manœuvre could be performed smoothly and without apparently disturbing the breathing rhythm. The samples were collected in evacuated 50 ml. ampoules and analysed in England.

RESULTS

Barometric pressure and altitude. The barometric pressure observed at various altitudes on Everest and comparable observations collected from the literature, are presented in Fig. 1. One can compare the results with the altitude-pressure curves given by Haldane & Priestley (1935*b*). Observations made on Everest in 1953, as well as those of Greene on Everest in 1933, show better agreement with the Zuntz curve than with the altimeter calibration curve. The same is true of observations made by physiological expeditions to high altitudes. The variations in barometric pressure due to meteorological causes were relatively small. Readings taken at the base camp (18,000 ft.) on 11 days between 12 April and 11 May varied only by 1·9 mm Hg, and readings taken at Camp III (20,500 ft.) on 8 days between 1 and 22 May varied by 2·3 mm Hg: the diurnal variations at these camps were less than 1·5 mm Hg. On the other hand, readings taken at Katmandu in March were about 7·5 mm Hg higher than readings taken in June after the monsoon had broken. The barometric pressure on the summit, when Hilary and Tensing were there on 29 May 1953, may be calculated from the barometric readings of Ward at Camp VII on 27–31 May, and temperatures recorded by Hillary which were as follows:

27 May	3.0 a.m.	Camp VII	24,000 ft.	−25° C
28 May	3.0 a.m.	Camp VIII	25,850 ft.	−25° C
29 May	3.0 a.m.	Camp IX	27,900 ft.	−27° C

Assuming a mean temperature of −26° C and a pressure of 308 mm Hg at 24,000 ft. the pressure at 29,000 ft. would be 250 mm Hg. In 1933 the pressure on the summit was probably somewhat higher. Greene's data fell exactly on the Zuntz curve, according to which the pressure at 29,000 ft. would be 269 mm Hg. His readings were 340, 337 and 334 mm Hg at 22,700 ft. and 305 mm Hg at 25,700 ft. The heights were determined by Spender with the theodolite (Greene, personal communication).

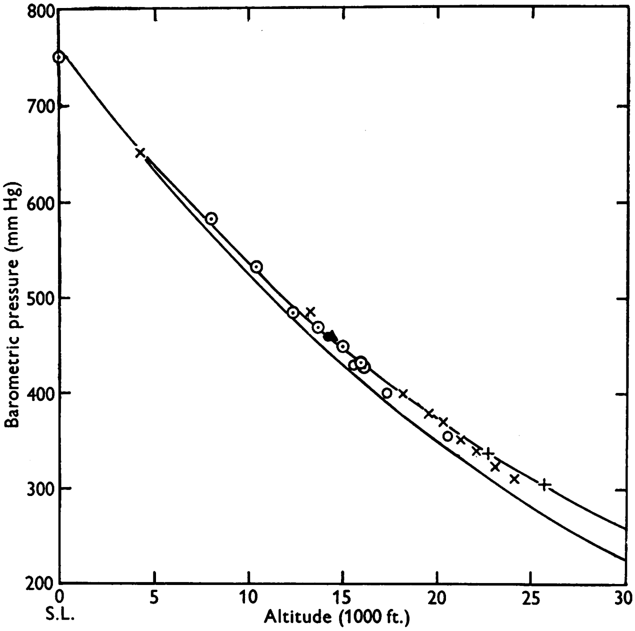

Fig. 1. Relation of barometric pressure to height. The upper curve is calculated from the formula proposed by Zuntz *et al.* (1906) using a mean temperature of 15° C; the lower curve is drawn according to the internationally adopted altimeter calibration which is based on a standard atmosphere; the plotted points represent observations made on Mount Everest and elsewhere. ×, 1953 Mount Everest expedition; +, 1933 Mount Everest expedition (Greene, 1934); ⊙, Peru (Hurtado & Aste-Salazer, 1948–49); ○, Andes (Dill *et al.* 1936); ●, Colorado (Douglas *et al.* 1913); ▲, Andes (Barcroft *et al.* 1923).

Resting ventilation. Fig. 2 shows the relation of resting ventilation to barometric pressure. The results have been compared with studies carried out in England in which serial measurements of resting ventilation were made on the same subject between the hours of 10.30 a.m. and 12.30 p.m. on several days. Each plotted point represents a single determination. At 18,000–21,200 ft. the minute volume at 'BTPS' (body temperature, pressure, saturated with water; Fed. Proc., 1950) varied from 13 to 22 l./min with a mean of 15·8 l./min as compared with a range of 5·5–9·8 l./min and a mean of 7·3 l./min at sea level. The corresponding respiratory rates were 16–20 (mean 18) and

9–18 (mean 13) respirations/min respectively. Lower respiratory rates usually of 14/min were recorded on other occasions above 18,000 ft. when ventilation was not being measured, and above 20,000 ft. Cheyne Stokes breathing was usual at night or after meals, the sequences in this subject consisting of six breaths separated by a 10 sec pause. Ventilation at altitudes over 18,000 ft. was, on the whole, higher in 1953 than in 1952, and this was associated with improved tolerance of altitude as judged by symptoms and physical performance. The minute volume at 'STPD' (Fed. Proc. 1950) was independent of altitude. This suggests that the resting oxygen consumption was also independent of altitude, as others have found (Houston & Riley, 1947). Gas samples were, however, taken on only two occasions; once in 1952 at 11,600 ft., which gave an oxygen consumption of 291 ml./min and an R.Q. of 0·91; and once in 1953 at 20,500 ft. when oxygen consumption of 325 ml./min was obtained. Sea-level values were 215–310 ml./min (mean 265) in twelve determinations with R.Q. of 0·98–0·71 (mean 0·85). In Fig. 3 the measurements of resting ventilation and the altitudes at which they were made are plotted against time. The values observed at 12,000–13,000 ft. on six successive mornings at the end of the approach march were strikingly consistent and were less variable than the results obtained in the laboratory at sea level. On 10 and 11 May after a month spent at 18,000 ft. minute volumes of 15·6 and 20·2 l./min were observed. On 11 May the subject went up to Camp III (20,500 ft.) and values of 22·1 and 21·9 l./min were observed there on the following two mornings. On the third morning a value of only 15·8 l./min was obtained, and later at Camp IV (21,200 ft.) a value of 17·2 l./min. Thus, at 18,000–21,200 ft., there

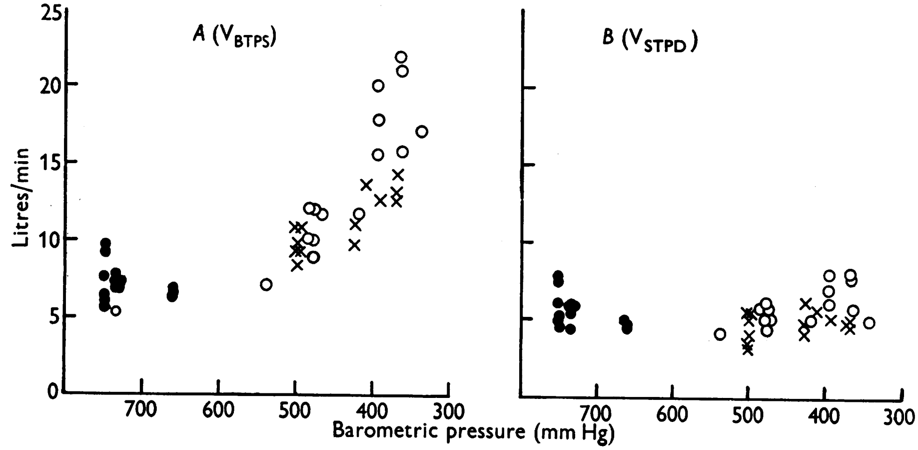

Fig. 2. Respiratory minute volume in a resting subject (G.P.) on the Cho Oyu expedition of 1952 (×); on the Everest expedition of 1933 (O); at sea level (●): (*A*) at 37° C observed pressure saturated (V_{BTPS}); (*B*) at 0° C, 760 mm Hg dry gases (V_{STPD}).

was no obvious relation between altitude and ventilation. On returning to base camp after spells at Camps III and IV, the subject noticed great relief of the effort of breathing, especially at night: and on going down to lower altitudes at the end of the expedition, some strikingly low minute volumes were observed. On the first morning at 10,000 ft., after two months at or above 18,000 ft., the minute volume was only 10 l./min and the respiratory rate was 7/min.

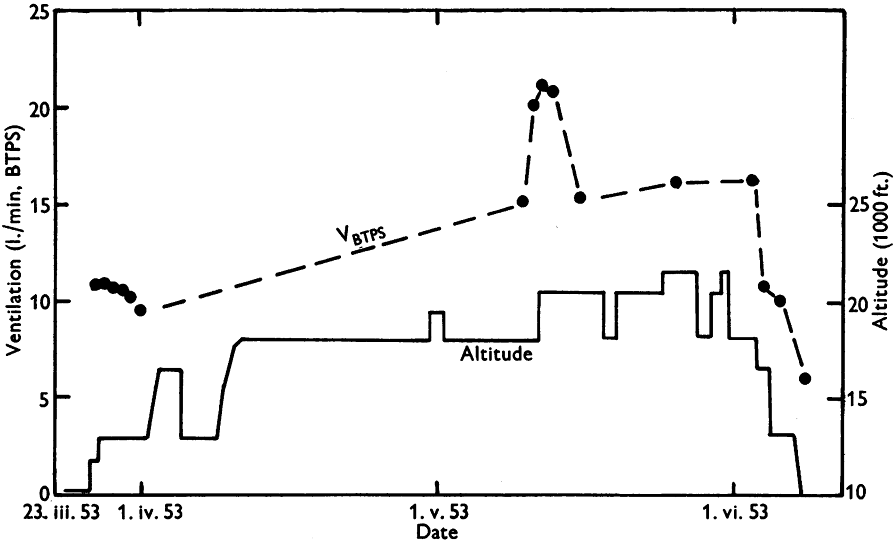

Fig. 3. Resting ventilation on Mount Everest, and altitude plotted against time.

Alveolar air. The results are presented in detail in Table 1 and are summarized in Tables 2 and 3. At base camp (18,000 ft.) where the mean alveolar O_2 tension was 44·5 mm Hg, everyone felt well and energetic; and most people felt tolerably well in the Western Cwm at Camp III (20,500 ft.) and Camp IV (21,200 ft.), where mean alveolar O_2 tensions of 43·5 and 39·3 mm Hg respectively were observed. At Camp VII (24,000 ft.), where the mean alveolar O_2 tension was 34·1 mm Hg, there was considerable impairment of mental function. Ward noted that routine procedures took much longer than usual to carry out, and anything requiring thought or dexterity such as tracing faults in the oxygen apparatus or repairing a Primus stove was accomplished with much effort and very slowly.

At Camp III (20,500 ft.), where the largest number of samples were taken, the intra-subject variation was 9 mm Hg for O_2 tension and 4 mm Hg for CO_2 tension. A difference of 9 mm Hg in alveolar O_2 tension at this altitude corresponds to an altitude difference of about 4000 ft. (Fig. 5). The variation between subjects was also considerable. The high values observed in C.W. are,

TABLE 1. Alveolar air at high altitude

Date	Place	Barometer (mm Hg)	Altitude (ft.)	Subject	CO_2 (vol. %)	O_2 (vol. %)	pCO_2 (mm Hg)	pO_2 (mm Hg)	Alveolar R.Q.	Time (hr)
29–30. ix. 53	London	759	Sea level	G.P.*	5·41	14·59	38·6	104·0	0·82	—
21. iv. 52	Namche	500	11,800	G.P.	7·81	12·38	35·4	56·1	0·89	—
22. iv. 52	Namche	500	11,800	G.P.	7·00	12·98	31·7	58·7	0·84	—
22. iv. 52	Namche	500	11,800	E.R.	5·92	13·70	26·8	62·1	0·77	—
22. iv. 52	Namche	500	11,800	T.B.	6·66	12·85	30·2	58·2	0·78	—
18. v. 52	Chule	425	15,500	G.P.	7·86	12·41	29·7	46·9	0·90	—
28. v. 52	Menlung La	370	20,000	G.P.	8·17	11·25	26·4	36·3	0·80	—
24. v. 52	Menlung La	370	20,000	R.C.	6·45	13·70	20·8	44·3	0·86	—
28. v. 52	Menlung La	370	20,000	R.C.	6·07	14·01	19·6	45·3	0·84	—
28. v. 52	Menlung La	370	20,000	R.C.	6·03	13·04	19·5	42·1	0·71	—
18. v. 52	Menlung La	370	20,000	C.S.	6·00	13·24	19·4	42·8	0·83	—
8. v. 53	Everest	397	18,000	G.P.	7·22	13·06	25·3	45·7	0·86	11.30
8. v. 53	Base Camp	397	18,000	G.P.	6·64	—	23·2	—	—	12.30†
8. v. 53	Base Camp	397	18,000	G.P.	7·24	13·15	25·3	46·0	0·91	14.10
8. v. 53	Base Camp	397	18,000	G.P.	7·80	—	27·3	—	—	14.20
8. v. 53	Base Camp	397	18,000	G.P.	6·51	—	22·8	—	—	14.30
30. iv. 53	Base Camp	397	18,000	M.P.W.	7·19	12·31	25·2	43·1	0·79	11.00
14. v. 53	Camp III	365	20,500	G.P.	8·26	11·46	26·3	36·4	0·99	21.05‡
15. v. 53	Camp III	365	20,500	G.P.	8·19	13·29	26·0	42·3	1·34	—
15. v. 53	Camp III	365	20,500	G.P.	8·59	12·20	27·3	38·8	0·97	—
15. v. 53	Camp III	365	20,500	G.P.	8·00	12·53	25·4	39·8	0·91	—
15. v. 53	Camp III	365	20,500	G.P.	7·70	13·40	24·5	42·6	0·87	—
15. v. 53	Camp III	365	20,500	G.P.	7·93	12·41	25·2	39·5	0·88	—
22. v. 53	Camp III	366	20,500	G.P.	7·58	13·26	24·1	42·2	0·97	16.00§
22. v. 53	Camp III	360	20,500	G.P.	7·95	12·55	25·3	39·9	0·93	16.10
23. v. 53	Camp III	365	20,500	G.P.	8·32	11·32	26·5	37·6	0·89	15.15
23. v. 53	Camp III	365	20,500	G.P.	7·79	12·59	24·8	40·0	0·91	15.30
23. v. 53	Camp III	365	20,500	G.P.	8·01	12·31	25·5	39·1	0·90	15.45
13. v. 53	Camp III	365	20,500	E.H.	6·48	12·62	20·6	40·1	0·73	20.50
13. v. 53	Camp III	365	20,500	E.H.	6·67	12·25	21·2	39·0	0·72	20.55
14. v. 53	Camp III	365	20,500	E.H.	5·68	13·98	18·1	44·5	0·77	07.30
15. v. 53	Camp III	365	20,500	C.W.	5·20	15·58	16·5	49·5	0·95	10.00
15. v. 53	Camp III	365	20,500	C.W.	6·17	14·07	19·6	44·7	0·87	11.00
15. v. 53	Camp III	365	20,500	M.W.	5·88	14·28	18·7	45·4	0·85	14.00
16. v. 53	Camp III	364·5	20,500	J.H.	6·44	12·86	20·5	40·9	0·75	20.15
16. v. 53	Camp III	364·5	20,500	J.H.	6·42	12·85	20·4	40·9	0·75	20.20
15. v. 53	Camp III	364·5	20,500	J.H.	5·24	15·59	16·7	49·6	0·96	17.00
24. v. 53	Camp IV	347	21,200	E.H.	7·20	12·35	21·6	37·1	0·80	20.00
31. v. 53	Camp IV	347	21,200	G.P.	6·76	13·81	20·3	41·4	0·93	15.00
3. v. 53	Camp V	337	22,500	M.P.W.	8·28	10·91	24·0	31·6	0·80	16.00
3. v. 53	Camp V	337	22,500	C.W.	6·60	13·51	19·1	39·2	0·85	16.00
3. v. 53	Camp V	337	22,500	C.E.	7·20	12·32	20·9	35·7	0·80	16.20
27. v. 53	Camp VII	308	24,000	M.P.W.	6·84	12·65	17·9	33·0	0·78	11.00
27. v. 53	Camp VII	308	24,000	W.N.	6·02	13·50	15·9	35·2	0·76	11.15

Mean of 5 samples. † Lunch 12.45 hr. ‡ Supper 19.00 hr. § Lunch 12.30 hr.

however, of doubtful significance, as this subject had difficulty in mastering the technical procedures. The lowest values at this altitude were observed in G.P. both in 1952 and 1953, and were associated with rather poor altitude tolerance.

TABLE 2. Alveolar air at 20,000–20,500 ft. Summary of results showing mean and range of values on individuals

Subject	No. of observations	Alveolar pO_2 (mm Hg) mean	Alveolar pO_2 (mm Hg) range	Alveolar pCO_2 (mm Hg) mean	Alveolar pCO_2 (mm Hg) range
		1953, Alt. 20,500 ft.	Bar. 365 mm Hg		
G.P.	11	39·8	36·4–42·6	25·5	24·1–26·5
E.H.	3	41·2	39·0–44·5	20·0	18·1–21·2
C.W.	2	47·1	44·7–49·5	18·1	16·5–19·6
J.H.	3	43·8	40·9–49·6	19·2	16·5–20·5
M.P.W.	1	45·4	—	18·7	—
Mean	—	43·5	—	20·3	—
		1952, Alt. 20,000 ft.	Bar. 370 mm Hg		
R.C.	3	43·9	42·1–45·3	20·0	19·5–20·8
G.P.	1	36·5	—	26·4	—
C.S.	1	42·8	—	19·4	—
Mean	—	41·1	—	21·9	—

TABLE 3. Mean alveolar gas tensions at altitudes above 17,000 ft.

Altitude (1000 ft.)	Bar. (mm Hg)	No. of subjects	No. of samples	Alveolar pCO_2 (mm Hg)	Alveolar pO_2 (mm Hg)	Alveolar R.Q.
		Himalayan expeditions 1952 and 1953				
18	397	2*	3	25·3	44·5	0·89
20	370	3	5	21·9	41·1	0·81
20·5	365	5	20	20·3	43·5	0·83
21·2	347	2	2	21·0	39·3	0·87
22·5	337	3	3	21·3	35·5	0·82
24·0	308	2	2	16·9	34·1	0·77
		Results by other workers				
17·5	401	10	—	25·6	42·3	0·76 Dill *et al.* 1936
20·1	356	9	—	21·4	37·7	0·76 Dill *et al.* 1936
21·0	360	1	1	21·0	39·6	0·77 Greene, 1934
21·2	360	2	2	17·8	42·8	0·73 Warren, 1939
22·7	337	1	3	17·7	40·7	0·87 Greene, 1934
22·8	337	2	3	15·6	37·0	0·60 Warren, 1939
25·7	305	1	1	9·2	43·0	0·79 Greene, 1934
20–21	350–330	4	—	21·4	36·9	— Houston & Riley, 1947†

* Data on C.W. omitted. † Alveolar effective air.

The relation of the alveolar gas tensions to barometric pressure is shown in Fig. 4, which is re-drawn from Fitzgerald's (1913) chart. Although Fitzgerald measured CO_2 tension only, O_2 tension being calculated from an assumed R.Q. of 0·83, her results have been confirmed by subsequent investigators whose data have been collected by Rahn & Otis (1949). In Fig. 4 the plotted points representing the mean values observed at each altitude on the Mount Cho Oyu and Mount Everest expeditions show fair agreement with the linear relationship predicted by Fitzgerald, except in the higher range of altitude, where the

O_2 values tend to lie above, and CO_2 values below, the straight line. The significance of this finding is brought out in Fig. 5, which shows alveolar O_2 tension plotted against altitude. If one assumes a limiting value for O_2 tension of 28 mm Hg, the straight-line relation gives an altitude limit of either 23,000 ft. or 25,000 ft., according to which pressure-altitude scale one uses. Fitzgerald predicted that a mountaineer on the summit of Mount Everest would have an alveolar O_2 tension of 24 mm Hg and a CO_2 tension of 19 mm Hg.

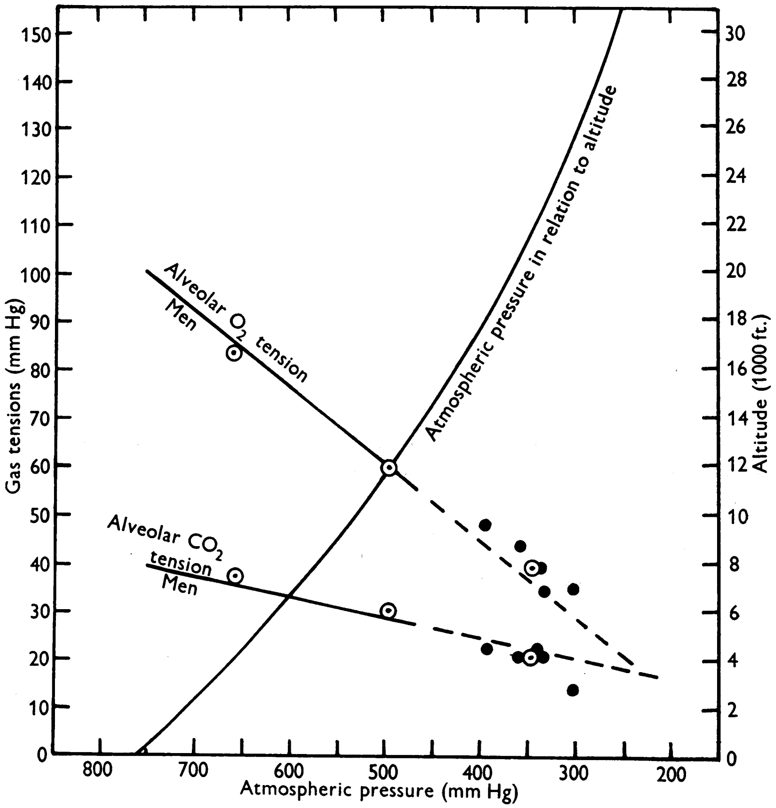

Fig. 4. Alveolar gas tensions in relation to barometric pressure and altitude. ●, Mean values for individuals, 1953, Everest; ⊙, mean values for individuals, 1952, Cho Oyu: the curve showing the relation of barometric pressure to altitude is calculated from Zuntz's formula.

Alveolar air in acclimatized versus unacclimatized men. Fig. 6 compares the present data with Boothby's (1944) data on unacclimatized men acutely exposed to simulated altitudes. The O_2 values in the Himalayan climbers were equivalent to those of unacclimatized men 4000–6000 ft. nearer sea level. Part of this advantage is, however, due to the fact that the barometric pressure at a given altitude in the Himalayas was somewhat higher than that indicated by the altimeter calibration scale used in aviation studies; heights

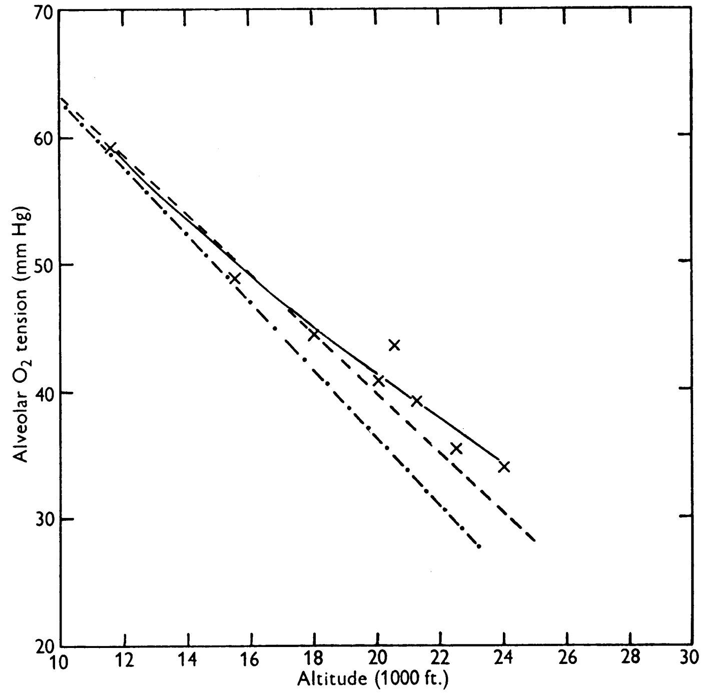

Fig. 5. Relation of alveolar O_2 tension to altitude. The continuous line is the curve fitted to the plotted points representing data obtained on the Mount Cho Oyu expedition, 1952, and the Mount Everest expedition, 1953. Interrupted lines show relation of alveolar O_2 tension and altitude predicted by Fitzgerald (1913) assuming a straight line relation between alveolar O_2 tension and barometric pressure (i) when height is calculated according to Zuntz's formula (- - - -), (ii) when height is calculated from the altimeter calibration formula (– • – – • –).

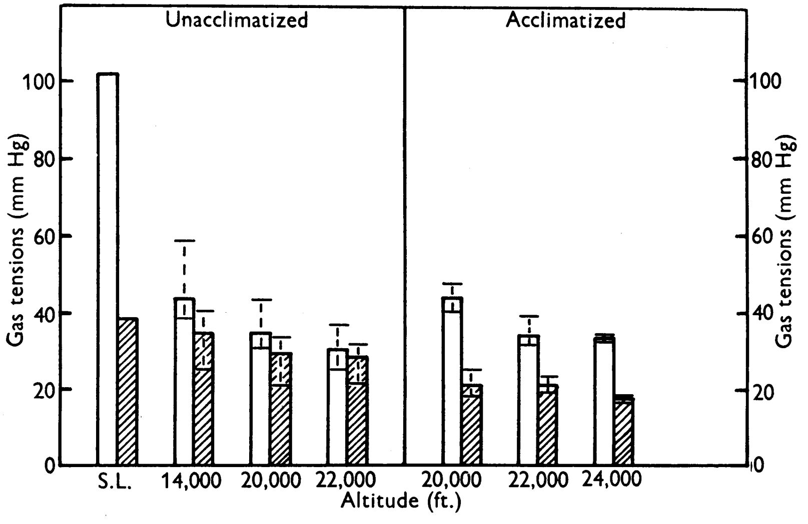

Fig. 6. Composition of alveolar air at various altitudes in unacclimatized acutely exposed subjects (Boothby, 1944) and in subjects acclimatized to altitude on Mount Cho Oyu and Mount Everest: □, O_2 tension; ▨, CO_2 tension. Mean and range of values are shown.

of 20,000 and 22,000 ft. on the altimeter scale being equivalent to 21,500 and 24,000 ft. in the Himalayas. Fig. 6 also illustrates the characteristically low CO_2 tensions of acclimatized men. The respiratory responses of the unacclimatized men were very variable, and in some subjects ventilation increased to levels comparable with those of acclimatized men.

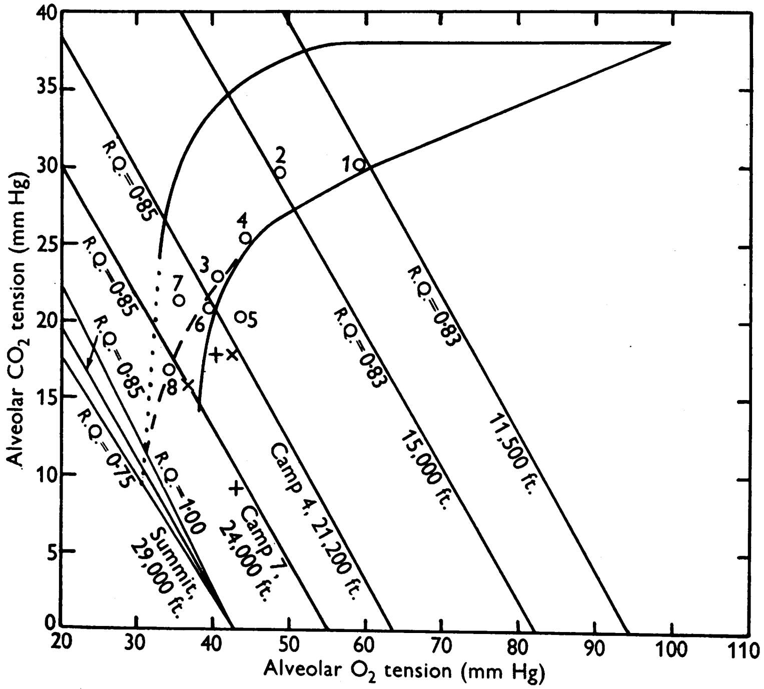

Fig. 7. The CO_2–O_2 diagram (Rahn & Otis, 1949) showing alveolar CO_2 tension and O_2 tension in unacclimatized men acutely exposed to altitude (upper curve), and in men acclimatized to altitude (lower curve). The numbered open circles represent mean values observed at the following altitudes (ft.) on the Mount Cho Oyu (1–3) and Mount Everest (4–8) expeditions: (1) 11,600, (2) 15,500, (3) 20,000, (4) 18,000, (5) 20,500, (6) 21,200, (7) 22,500, (8) 24,000. Crosses represent data from pre-war Everest expeditions, viz. +, Greene (1934); ×, Warren (1939). The oblique lines are lines on which alveolar O_2 tension at a given altitude and R.Q. must lie; they take origin from the inspired O_2 tension at the altitude stated. The interrupted curve has been drawn by eye to fit the 1953 data. Difference between unacclimatized and acclimatized men is maximal at 11,500–15,000 ft., and disappears at 29,000 ft., where predicted O_2 tension is about 32 mm Hg.

In Fig. 7 the Himalayan data are plotted on the Fenn CO_2–O_2 diagram and are compared with the curves of Rahn & Otis (1949) representing the composition of alveolar air in unacclimatized men acutely exposed to altitude and in men acclimatized to altitude. Iso-altitude lines for 21,200 and 24,000 ft., based on observed barometric pressures and an R.Q. of 0·85, are shown, as well as iso-altitude lines for 29,000 ft. and various R.Q. These lines have been calculated from the alveolar gas equation

$$\text{R.Q.} = \frac{0{\cdot}791\text{pCO}_2}{0{\cdot}209(B-47-\text{pCO}_2)-\text{pO}_2}.$$

At a given altitude and R.Q. the alveolar air values must be on the corresponding iso-altitude line, the origin of which is at the inspired O_2 tension. The upper curve in Fig. 7 shows the response of unacclimatized men to acute exposure to altitude. There is no increase in ventilation until an alveolar O_2 tension of 50–60 mm Hg is reached, which corresponds to an altitude of 12,000 ft. or inhalation of 13% O_2; consequently, the O_2 tension falls progressively, but CO_2 tension remains unchanged: the onset of hyperpnoea is shown by the downward turn of the curve indicating a lowering of CO_2 tension and a reduced change in O_2 tension. The lower curve shows the response of acclimatized persons. Increased ventilation is present from alveolar O_2 tensions of 100 mm Hg downwards; at the higher altitudes the respiratory response is much greater in acclimatized persons and consequently, at a given altitude, O_2 tension is considerably higher and CO_2 tension lower, than in the unacclimatized acutely exposed subject.

The present results show good agreement with the Rahn & Otis curve for acclimatized men up to 18,000 ft. Above that the plotted values deviate to the left in the manner predicted by Rahn & Otis for partially acclimatized persons. An arbitrary curve drawn to fit these data cuts the isopleth for the summit of Mount Everest (29,028 ft.) at 32 mm Hg and almost coincides with the extrapolated curve for unacclimatized persons. The iso-altitude lines for different R.Q. show that a high metabolic R.Q. is of no advantage in maintaining the alveolar O_2 tension at 29,000 ft., although it would be an advantage at less extreme altitudes, where the alveolar curve is less steep. The significance of this point is that mountaineers have a craving for sugar and sweet foods at high altitude (Pugh, 1954).

The effect of O_2 *on alveolar* CO_2 *tension.* The results of the experiment at 18,000 ft. are shown in Table 4. The mean CO_2 tension during the control period was 26 mm Hg and the mean O_2 tension 45 mm Hg. While breathing O_2 the CO_2 tensions were more regular and showed a steady upward trend, reaching a level of 30 mm Hg: this suggested improved respiratory regulation and a slow decrease in CO_2 sensitivity. The first three pCO_2 values after starting to breathe O_2 were above the average of the control values. This finding, coupled with improved regulation of CO_2 tension during O_2 breathing, suggested that in this subject hypoxic chemoreceptor stimulation was still present even after 4 weeks at 18,000 ft.

The alveolar CO_2 tension observed in the same subject on 3 successive days at 20,500 ft. are shown in Table 5. Each day the CO_2 tension while the subject was breathing O_2 was lower than it had been while breathing O_2 on the previous day; the CO_2 tension when he was breathing O_2 was higher than when he was breathing air on the second day, but not on the third day. These results suggest a progressive increase in CO_2 sensitivity, although, in view of the variability of resting ventilation, no definite conclusion is justified.

TABLE 4. Effect of breathing oxygen on alveolar gases. Results of an experiment done at base camp on Mount Everest; 18,000 ft.; bar. 397 mm Hg.; subject, G.P.

		Composition of alveolar gases				
Observation no.	Time	CO_2 (%)	O_2 (%)	pCO_2 (mm Hg)	pO_2 (mm Hg)	Time elapsed (min)
1	11.30	7·14	12·96	25·3	44·3	—
		7·30	12·97	—	—	—
2	12.00	6·61	—	—	—	—
		6·66	—	23·3	—	—
3	14.10	7·24	13·05	25·3	45·7	—
4	14.20	7·80	—	27·3	—	—
5	14.30	6·51	—	22·8	—	—
			Mean	25·8	45·0	—
	14.55	Started breathing O_2, 2 l./min				0
6	14.57	7·57	51·37	26·5	179·8	2
7	15.10	7·78	58·53	27·2	204·9	15
8	15.27	7·75	52·32	27·2	183·1	32
9	15.55	7·79	44·11	27·3	154·4	60
10	16.55	8·22	39·54	28·8	138·4	120
11	17.15	8·59	33·0	30·1	115·5	140
			Mean	27·9	162·7	—

TABLE 5. Effect of breathing oxygen for 10 min on alveolar CO_2 tension on successive days at 20,500 ft.; subject, G.P.

	Alveolar pCO_2 (mm Hg)	
Date	Breathing air	Breathing pure oxygen
21. v. 53	—	29·2
22. v. 53	24·6	27·8
23. v. 53	26·1	25·6

The data on the effect of using O_2 for sleeping purposes (Table 6) show a rise in CO_2 tension of 3–5 mm Hg during the night, and an immediate return to the pre-oxygen levels within half an hour of taking the apparatus off. The results on J.H. suggest that the rise in CO_2 tension may have been an immediate effect rather than a slow trend. J.H. was the only subject to attain sea-level alveolar O_2 tensions; in the other subjects the alveolar O_2 tensions were between 50 and 80 mm Hg. This was explained by the fact that J.H. on this occasion received 2 l. O_2/min, whereas the other subjects shared a 2 l. supply between them. The subjective effect of breathing oxygen even in relatively low concentrations was remarkably good. One slept more soundly than usual in spite of the mask, and awoke conspicuously refreshed. The feeling of increased energy after a night on oxygen lasted 2 or 3 hr.

Table 6. Composition of alveolar air in subjects using open circuit oxygen apparatus for sleeping

				Alveolar air			
Date	Subject	Time	Conditions	CO_2 (vol. %)	O_2 (vol. %)	pCO_2 (mm Hg)	pO_2 (mm Hg)
		1952; 20,000 ft. Barometric pressure 370 mm Hg					
26. v. 52	R.C.	19.05	Breathing air	6·45	13·70	20·8	44·3
27. v. 52	R.C.	02.05	5 hr breathing O_2, 1·0 l./min	8·36	20·03	27·0	64·7
26. v. 52	T.B.	19.00	Breathing air	—	—	—	—
26. v. 52	T.B.	02.00	5 hr breathing O_2, 1·0 l./min	8·20	29·68	26·5	95·9
		1953; 20,500 ft. Barometric pressure 365 mm Hg					
13. v. 53	E.H.	20.50	Breathing air	6·48	12·62	20·6	40·1
		20.55	Breathing air	6·67	12·25	21·2	39·0
14. vi. 53	E.H.	06.00	8 hr breathing O_2, 1·0 l./min	7·22	18·47	23·0	58·7
		06.05	8 hr breathing O_2, 1·0 l./min	7·33	19·56	24·6	62·2
		07.30	30 min breathing air	5·68	13·90	18·1	44·2
13. v. 53	G.P.	21.05	Breathing air	8·26	11·46	26·3	36·4
14. v. 53	G.P.	05.55	8 hr breathing O_2, 1·0 l./min	9·90	25·31	31·5	80·5
		06.15	8 hr breathing O_2, 1·0 l./min	10·57	21·11	33·6	67·1
		06.20	8 hr breathing O_2, 1·0 l./min	9·19	18·14	29·2	52·7
16. v. 53	J.H.	20.15	Breathing air	6·44	12·86	20·4	40·8
		20.20	Breathing air	6·42	12·85	20·4	40·8
		20.25	Began breathing O_2, 2 l./min	—	—	—	—
		20.38	Breathing O_2, 2 l./min	7·69	38·50	24·4	122·2
		20.50	Breathing O_2, 2 l./min	7·42	36·60	23·6	116·2
17. v. 53	J.H.	06.00	8 hr breathing O_2	7·93	33·65	25·2	106·8
		06.05	Breathing O_2, 2 l./min	8·11	31·17	25·7	98·9
		07.00	50 min breathing air	6·31	13·45	20·0	42·7

DISCUSSION

The relation of barometric pressure to height was discussed by Zuntz *et al.* (1906) in connexion with their physiological studies on Monte Rosa, and again by Fitzgerald (1913) in connexion with the Pike's Peak expedition. Fitzgerald showed that the barometric pressure observed in mountains in various parts of the world corresponded closely with the pressures calculated from the formula proposed by Zuntz when a mean temperature of 15° C was assumed. Later Haldane & Priestley (1935*b*) pointed out that at altitudes above 15,000 ft. the barometric pressures calculated from this formula exceed those calculated from the internationally adopted altimeter calibration by an increasing amount. The matter is of some importance in high altitude studies if one wishes to compare observations made in the decompression chamber with observations made on mountains, since the atmospheric pressures corresponding with the stated altitudes will not be the same. For example, 20,000 ft. in the decompression chamber (pressure 350 mm Hg) is equivalent to 22,000 ft. on a mountain, and 29,000 ft. in the decompression chamber (pressure 236 mm Hg) would be equivalent to 34,000 ft. on a mountain. Again, the barometric pressure on the summit of Everest according to the altimeter scale would be 236 mm Hg, whereas according to Zuntz's formula it would be 269 mm Hg. Hillary and Tensing did not take an aneroid with them on their climb to the summit in 1953, but calculating from observations at 24,000 ft. it can be assumed that the barometric pressure there was within a few millimetres of 250 mm Hg. In 1933, the pressure was probably nearer 269 mm Hg, since Greene recorded a reading of 305 mm Hg at 25,700 ft. (compare 308 mm Hg at 24,000 ft. in 1953), which corresponds closely with Zuntz's curve. The relatively high barometric pressure that year must have been of great assistance to Shipton, Smythe, Wager and Wynne Harris, all of whom climbed without oxygen apparatus to 28,100 ft. (Ruttledge, 1934). At these great heights, where man is working near his limit, small differences in barometric pressure are of great significance. This is borne out by the large increase in the effort of climbing and the rate of physical deterioration at each camp above 24,000 ft., although the actual difference in altitude from one camp to the next is not more than 1000–1500 ft. which at 24,000 ft. is equivalent to a difference in barometric pressure of only 22–33 mm Hg.

The data presented in this paper, as well as the observations made on physiological expeditions, confirm the findings of both Fitzgerald and Haldane. They also indicate that the formula they used is a better guide to barometric pressure in mountains than the accepted formula for calibrating altimeters. Both formulae are based on the same fundamental relation but the constants are slightly different. This point is made clear by expressing the equations in the same mathematical form. If h is the height in feet, P is the barometric pressure in mm Hg at height h and t is mean temperature in ° C, Zuntz's formula becomes

$$\log\frac{760}{P}=\frac{h}{236{\cdot}22\,(256{\cdot}4+t)},$$

where $t=15^\circ$ C, and the altimeter calibration formula becomes

$$\log\frac{760}{P}=\frac{h}{221{\cdot}15\,(273+t)},$$

where t is calculated from the standard atmosphere. It seems likely that the constants in the formula used by Fitzgerald were originally chosen to make the formula fit conditions in mountains rather than free air. No details, however, are given by Zuntz as to how the formula was derived.

The discrepancy between the altimeter scale and observations in mountains is explained by the fact that expeditions to high mountains naturally operate at a season when relatively warm, fine weather at the higher altitudes is to be expected. Under such conditions, mean temperatures based on the standard atmosphere are likely to be too low, as also may be the sea-level barometric pressure of 760 mm Hg. To give an example, the night temperature of −27° C observed at 27,900 ft. on Mount Everest may be compared with the standard temperature for this height which is −40° C. The corresponding sea-level temperature calculated from a lapse rate of 1·98° C per 1000 ft. would be +31° C, compared with +15° C according to the standard atmosphere. It is worth mentioning that minimum night temperatures of +20° C were observed at 1000 ft. on the plain below the Himalayan foothills in April 1922. If one takes 760 mm Hg as the sea-level pressure, +27° C as the sea-level temperature, and −29° C as the temperature at 29,000 ft., the resulting barometric pressure is 249·5 mm Hg, which agrees closely with the value obtained by the more accurate method of calculating from observations at 24,000 ft.

Ventilation. The measurements of minute volume bring out in a general way the increase in minute volume with altitude. No strict comparison can be made between the values observed above 18,000 ft. in 1952 and 1953 because the times spent at altitude and the apparatus used were different. The higher values in 1953 do, however, raise the question whether an increased respiratory response may not partly account for the improvement in acclimatization which all climbers notice on their second visit to the Himalayas. The normal variability of resting ventilation (except under carefully controlled conditions) is such that one should not expect to see any close relationship with relatively small changes of altitude, particularly at the higher altitudes where the change in barometric pressure with altitude is considerably less than at sea level. Nor should one expect to demonstrate the progressive increase in ventilation over the first few days of a visit to high altitude which others have reported. The fall in ventilation observed in G.P. immediately on descending is contrary to expectation. Others have found that hyperpnoea persists for several days after descending to sea level after a sojourn at high altitudes. It is possible that respiratory adjustments are more rapid in climbers moving frequently from one altitude to another than in a party ascending or descending after a prolonged stay at a particular altitude. The reports of members of the party on Mount Everest suggested, however, that the response to changes of altitude would be found to vary widely in different individuals. Whereas G.P. noticed immediate relief of breathing on descending to lower altitude, two other climbers reported shortness of breath (though only during exercise), and J.H. complained of unpleasant attacks of suffocation at night on returning to Thyangboche (13,000 ft.) after 5 days spent above 18,000 ft. and on two other occasions at base camp (18,000 ft.) after visits to 20,000–26,000 ft.

Although ventilation in litres 'BTPS' was approximately doubled both in range and mean value at 18,000–21,200 ft. compared with the sea-level values, the 'STPD' values were independent of altitude. Hence ventilation was so regulated that the mass of gas breathed was independent of altitude and the reduced density of the air and increased volume of water vapour in the lungs at altitude was completely compensated. Respiratory compensation for reduced atmospheric pressure as opposed to density is, of course, impossible above 10,000 ft., where inspired O_2 tension is the same as alveolar O_2 tension at sea level. The finding that ventilation was independent of altitude when expressed in litres 'STPD' also suggests that metabolism was unchanged, and this was supported by such measurements as were made.

Alveolar air. Haldane–Priestley end-expiratory samples have proved of value over many years for following respiratory adaptation to altitude. Although not much confidence can be placed on single samples, average results based on a number of samples on one or more individuals have given very consistent results. Alveolar CO_2 tension is a useful measure of any changes in ventilation; and if metabolism is known, alveolar ventilation and respiratory minute volume can be computed from the alveolar gas tensions by the equation of Fenn, Rahn & Otis (1946). The rather large and variable alveolar-arterial O_2 gradient observed in resting subjects at sea level is greatly reduced at high altitude. Houston & Riley (1947), in their chamber study, 'Operation Everest', observed a mean alveolar-arterial O_2 gradient of $+1{\cdot}1$ mm Hg (range -5 to $+5$) at 18,000 ft. and above, compared with 13 mm Hg (range $+3$ to $+23$) at sea level; and Dill and others on the physiological expedition to Chile (1936) observed a mean alveolar-arterial O_2 gradient of $+2{\cdot}8$ mm Hg (range $-2{\cdot}4$ to $+9{\cdot}32$) at 20,000 ft. Alveolar O_2 tension is therefore nearly as good an index of O_2 lack at altitude as direct measurements on arterial blood.

The mean alveolar gas tensions observed on the 1953 Everest expedition at 21,200–22,500 ft. (Bar. 347–337 mm Hg), which were 21·1 mm Hg for CO_2 and 37·4 mm Hg for O_2 respectively, are comparable with the results of Dill and others at a slightly lower altitude (20,000 ft., Bar. 356 mm Hg) and agree closely with the data for 'effective alveolar air' obtained over a comparable range of pressures by Houston & Riley (1947). The samples brought back by Greene (1934) and Warren (1939) from previous Everest expeditions tend to show higher O_2 tensions and lower CO_2 tensions than the present data, but some of their R.Q. are suspiciously low. There is no evidence, however, from the time spent at altitude or physical performance that previous parties were better acclimatized than the 1953 party.

Rahn & Otis (1949) used the data of Greene (1934) and Warren (1939) in calculating the O_2–CO_2 curve for acclimatized men at altitudes over 21,000 ft.; consequently the curve fitted to the present data lies somewhat to the left of their curve, suggesting less complete adaptation. It is open to question, however, whether a steady respiratory state is ever reached at these altitudes;

whether further data would not show respiration to be essentially variable and poorly regulated at these altitudes. Extrapolation from the present data suggests that men on the summit of Mount Everest would respond very like unacclimatized acutely exposed persons and would have alveolar O_2 and CO_2 tensions of about 32 and 12 mm Hg respectively. The corresponding arterial O_2 saturation, assuming a pH of 7·6 (Houston & Riley, 1947), would be about 55%, which is within the range of values observed by Dill *et al.* (1936), and Houston & Riley (1947) in subjects at 20,000 ft. Such values are certainly consistent with normal consciousness in partially acclimatized persons, although there is impairment of other mental functions. Unacclimatized acutely exposed subjects, on the other hand, usually lose consciousness when the arterial O_2 saturation falls below 60% (Pappenheimer, 1944). In the event Hillary found he could walk around easily on the summit of Everest without extra oxygen and took some excellent photographs. However, after 10 min he began to get confused, and put himself on oxygen again. A thousand feet lower down, where the barometric pressure would be only about 10 mm Hg higher than on the summit, he and Tensing had been able to work steadily for 10 min at a time in preparing a site for their tent without their oxygen apparatus and had spent much of the night without extra oxygen.

Effect of oxygen. In planning oxygen equipment for use on Everest one of the risks envisaged was the possibility that the prolonged use of oxygen might cause significant loss of acclimatization. This factor, added to absence of the normal respiratory adaptation during an ascent, might result in serious loss of efficiency if not loss of consciousness if the oxygen supply were to run out above 28,000 ft. The present data do not suggest any important loss of acclimatization, as evidenced by the CO_2 response, and the subjective effects were so good that mountaineers now consider that extra oxygen at night is more important to them on mountains over 25,000 ft. than oxygen for climbing.

The rise in CO_2 tension which took place immediately on going on to oxygen showed that the subjects were still responding to anoxic stimulation at 18,000–21,000 ft. which is evidence that they were incompletely acclimatized. It is doubtful, however, if mountaineers ever reach a stable condition at any given altitude above 18,000 ft. since they seldom spend more than a few days in one place and their daily stint of climbing involves changes of altitude of 1000–3000 ft. Climbing parties have, however, spent up to 6 weeks without going below 20,000 ft. On Everest in 1953 men who spent many weeks continuously above 20,000 ft. did not consider that they could have remained at 20,000 ft. indefinitely. The reasons were the same as those given by miners on Auconquilcha who refused to occupy a camp built for them at 19,000 ft. (Matthews, 1954), namely, loss of sleep and failure of appetite. The response of climbers suggests, however, that partial acclimatization certainly occurs at altitudes up to 23,000 ft. and possibly up to 25,000 ft., but is associated with an underlying process of physical deterioration, which eventually compels the climber to descend.

SUMMARY

1. Barometric pressures observed on expeditions to high mountains are higher than the corresponding pressures calculated according to the standard altimeter calibration. The difference has considerable physiological significance above 18,000 ft.

2. Resting ventilation ('BTPS') rose to 13–22 l./min (mean 15·8 l./min) above 18,000 ft. compared with 5·5–9·8 l./min (mean 7·3 l./min) at sea level. Ventilation at 'STPD' was independent of altitude. Persistent hyperpnoea on descending to lower altitude was not observed in the subject studied, and the reports of other members of the party suggested that individual responses to changes of altitude were highly variable.

3. Observations on the composition of alveolar air at various altitudes up to 24,000 ft. are reported and compared with previous data from the literature. At 24,000 ft. (Bar. 308 mm Hg) alveolar CO_2 tension was 16·8 mm Hg and alveolar O_2 tension 34·1 mm Hg.

4. The response to supplementary O_2 at 18,000 ft. and above consisted of (1) a small immediate rise in CO_2 tension showing that hypoxic stimulation of breathing had still been present; and (2) a slow rise over many hours, suggesting loss of acclimatization. However, the CO_2 tension quickly reverted to pre-oxygen levels on discontinuing O_2. The subjective effects of breathing O_2 during the night are described.

REFERENCES

Barcroft, J., Binger, C. A., Bock, A. V., Doggart, J. H., Forbes, H. S., Harrop, G. A., Meakins, J. C. & Redfield, A. C. (1923). Observations on the effect of high altitude on the physiological processes of the human body, carried out in the Peruvian Andes. *Phil. Trans.* **211**, 351–480.

Boothby, W. M. (1944). *Handbook of Respiratory Data in Aviation.* Washington: Office of Scientific Research and Development.

Dill, D. B., Christensen, E. H. & Edwards, H. T. (1936). Gas equilibria in the lungs at high altitudes. *Amer. J. Physiol.* **115**, 530–538.

Douglas, C. G., Haldane, J. S., Henderson, Y. & Schneider, E. C. (1913). Physiological observations made on Pike's Peak, Colorado, with special reference to adaptation to low barometric pressures. *Phil. Trans.* B, **203**, 185–318.

Fed. Proc. (1950). Standardization of definition and symbols in respiratory physiology. *Fed. Proc.* **9**, 602–605.

Fenn, W. O., Rahn, H. & Otis, A. B. (1946). A theoretical study of the composition of alveolar air at altitude. *Amer. J. Physiol.* **146**, 637–653.

Fitzgerald, M. P. (1913). The changes in the breathing and the blood at various high altitudes. *Phil. Trans.* B, **203**, 351–371.

Greene, R. (1934). Observations on the composition of alveolar air on Everest, 1933. *J. Physiol.* **82**, 481–485.

Gulatee, B. L. (1954). *The Height of Mount Everest.* Survey of India Technical Paper no. 8. Published by order of the Surveyor General of India.

Haldane, J. S. & Priestley, J. G. (1935*a*). *Respiration*, 2nd ed. p. 18. Oxford: Clarendon Press.

Haldane, J. S. & Priestley, J. G. (1935*b*). *Respiration*, 2nd ed. p. 323. Oxford: Clarendon Press.

Houston, C. S. & Riley, R. L. (1947). Respiratory and circulatory changes during acclimatization to high altitude. *Amer. J. Physiol.* **149**, 565–588.

Hurtado, A. & Aste-Salazar, H. (1948–49). Arterial blood gases and acid-base balance at sea level and at high altitude. *J. appl. Physiol.* **1**, 304–325.

Hunt, J. (1953). *The Ascent of Everest*, 1st ed. pp. 236–237. London: Hodder and Stoughton.

Matthews, B. (1954). Limiting factors at high altitude. *Proc. Roy. Soc.* B, **113**, 1–4.

Orsini, D. & Passmore, R. (1951). The energy expended carrying loads up and down stairs: experiments using the Kofranyi-Michaelis Calorimeter. *J. Physiol.* **115**, 95–100.

Pappenheimer, J. R. (1944). Arterial oxygen saturation at altitude. *Handbook of Respiratory Data in Aviation.* Washington: Office of Scientific Research and Development.

Pugh, L. G. C. E. (1953). Technique employed for measuring respiratory exchanges on Mount Everest, 1953. *J. Physiol.* **123**, 25–26*P*.

Pugh, L. G. C. E. (1954). Himalayan rations with special reference to the 1953 expedition to Mount Everest. *Proc. Nutr. Soc.* **13**, 60–69.

Rahn, H. & Otis, A. B. (1949). Man's respiratory response during and after acclimatization to high altitude. *Amer. J. Physiol.* **157**, 445–462.

Ruttledge, H. (1934). *Everest*, 1933, pp. 135–170. London: Hodder and Stoughton.

Scholander, P. F. (1947). Analyzer for accurate estimation of respiratory gases in one-half cubic centimeter samples. *J. biol. Chem.* **167**, 235–250.

Warren, C. B. M. (1939). Alveolar air on Mount Everest. *J. Physiol.* **96**, 34–35*P*.

Zuntz, N., Loewy, A., Müller, F. & Caspari, W. (1906). *Höhenklima und Bergwanderungen*, p. 38. Berlin: Deutsches Verlagshaus.