

HEMATIC AND CARDIOPULMONARY CHARACTERISTICS OF THE ANDEAN MINER¹

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Miners working at high altitudes are exposed to severe oxygen deficiency (hypoxia). As a result, altitude sickness (Monge's disease) is widespread among them. The author suggests a need for vigorous periodic and pre-employment examination of such miners, and the desirability of mechanized mining methods at these altitudes.

Introduction

The influence of Peru's high altitudes on the human organism was originally described in 1928 by Monge (1). His works discuss the morphological and physiological characteristics of highland dwellers, and the genetic characteristics inherited from a race of a people which had inhabited those regions for centuries. Subsequent studies by Hurtado (2), and later by other authors (3), provided a fuller understanding of the physiological and biochemical characteristics of these people. In the same year, Monge described the clinical features of a type of altitude sickness now known as "Monge's disease."

Persons working high above sea level have a number of adaptive hematic, circulatory, and respiratory mechanisms to offset low oxygen pressure and maintain an adequate supply of oxygen to the tissues (1). For example, Hurtado (2) has demonstrated a close relationship between hemoglobin levels and altitude; but this mechanism is not always a compensatory one, since on some occasions it interferes with the normal functioning of the body. There is also a special enzymatic mechanism in the cells which permits better oxygen utilization.

In general, exposure of high-altitude dwellers to severe hypoxic tension triggers a series of regulatory mechanisms. In some cases these

mechanisms bring the person into adequate physiological balance with his environment; in others this balance is upset by a disproportionate response from the regulatory mechanism, producing individuals subclinically and clinically ill-adapted to altitude (Monge's disease). Unfortunately, owing to unfamiliarity with these problems, Peru's mines give employment to physiologically inadequate workers, leading to sometimes fatal consequences.

Special physiological and cardiopulmonary characteristics of high-altitude dwellers are reflected in respiratory processes, and show up in electrocardiographic and anatomic-pathologic studies. With regard to the respiratory function (4-8) there is an increase in lung ventilation, a growth in both static and dynamic lung volumes, a rise in the ratio of residual lung volume to total lung capacity, and an increase of diffusion capacity. Electrocardiographic features (9-13) include varying degrees of right ventricular hypertrophy, disturbance conduction in the right bundle branch, and a pressure increase in the pulmonary circuit (14-16). Anatomic-pathologic studies have revealed hypertrophy of the right ventricle (17), structural modifications of a congenital nature in the small pulmonary blood vessels (18-19), and modifications in the lungs' alveolar wall (20).

This paper presents the results of several studies of high-altitude miners aimed at determining what hematic and cardiopulmonary features should be sought in selecting miners of this variety, especially those who will have to work in an environment containing silica dust.

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Hematic Features

In one study of seven mining centers at different altitudes (21), 2,167 workers considered free of silicosis were interviewed. Table 1 shows the number of workers studied in each mine, the altitude of the mine, average hemoglobin levels, and the standard deviation for each altitude.

Figure 1 is based on data in Table 1 relating altitude with the average hemoglobin level. The mathematical formula relating these two variables (shown in the figure) corresponds to a vertical parabola described by the equation:

$$Y = 13.40 + 0.55 \left(\frac{X}{1000} \right)^{1.66}$$

where Y is the average hemoglobin level in g/100cc and X is the height above sea level in meters (20). Figure 1 also depicts average hemoglobin levels—curves corresponding to two and three standard deviations (including 95.46 per cent and 99.73 per cent of the hemoglobin levels measured, respectively)—and shows the limits of the zones of anemia and erythremia. The general trend of the central curve shows that anemia cases become scarcer as altitude increases, there being an altitude limit (3,450 m

above sea level) at which no cases of anemia were found. Higher up, at altitudes above 3,750 m, severe cases of erythremia (persons with hemoglobin levels above 23 g/100 cc of blood) begin to appear. Going on the basis of these statistical calculations, it may be said that there is a region of "critical altitude," already mentioned by Hurtado, in which hypoxic stimulus causes the body to reach the limit of normal hematopoietic response.

The region between 3,450 m and 3,750 m yielded no cases of either anemia or erythremia, and is considered the maximum altitude zone for mining work under sound physiologic conditions.

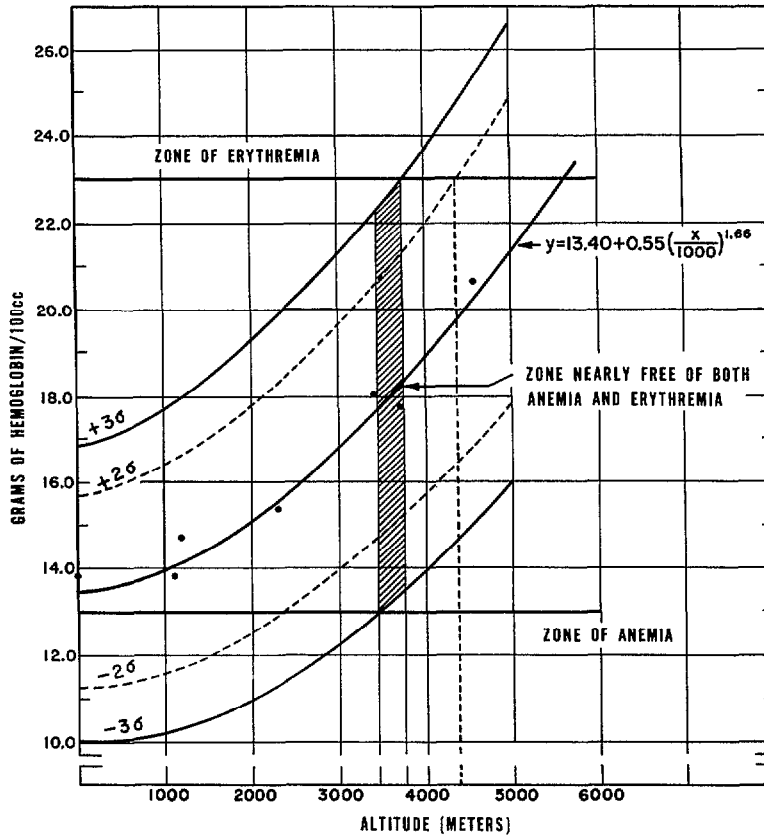
In this region mining is impossible for anemic individuals, as the circulatory system's means of compensating for anemia appear pushed to the limit. The hypoxic stimulus at this altitude range also causes a hematic response, which remains within normal limits.

The region between 3,750 m and 4,000 m is another zone of biological interest. Here the number of persons with hemoglobin levels above 23 g per 100 cc of blood is minimal, the body can adjust to environmental conditions, and hypoxic overloading is apparent only in a small percentage of cases.

TABLE 1—Relationship of hemoglobin levels with altitude in healthy workers 20-40 years old.

Hemoglobin (grams per 100 cc)	Isla Chinchá		Chilote		Ancos		Arequipa		Pasto Bueno		Buldibuyo		San Antonio	
	Cases	%	Cases	%	Cases	%	Cases	%	Cases	%	Cases	%	Cases	%
< 11	1	0.3							1	0.2				
11-12.9	63	19.7	58	22.5	10	9.6	9	3.4	1	0.2				
13-14.9	218	68.1	169	65.5	46	44.2	87	32.5	5	1.2	6	2.2	1	0.2
15-16.9	38	11.9	31	12.0	47	45.2	143	53.4	78	19.1	59	21.8	5	0.9
17-18.9					1	1.0	28	10.3	226	55.5	169	62.4	64	11.9
19-20.9							1	0.4	90	22.1	35	12.9	258	47.9
21-22.9									7	1.7	2	0.7	173	32.2
23-24.9													31	5.8
25-26.9													6	1.1
Total	320	100	258	100	104	100	168	100	408	100	271	100	538	100
Maximum value	16.70		15.84		17.71		19.20		22.00		21.40		26.30	
Minimum value	10.80		11.10		11.70		11.00		10.00		13.60		14.30	
Mean value	13.83		13.79		14.75		15.44		18.04		17.76		20.65	
Standard deviation	1.13		1.16		1.34		1.41		1.54		1.34		1.70	
Altitude (in meters)	10		1,130		1,200		2,300		3,475		3,720		4,600	

FIGURE 1—The curve relating average hemoglobin value to altitude; a mathematical formula relating these two variables; the zone in which no cases of anemia or erythremia were found (shaded area); and the maximum altitude (vertical dotted line) at which mining work may be conducted (given sound physiologic conditions).



Above 4,400 m the number of severe erythremia cases grows progressively, indicating that the individual's hematopoietic response reaches a limit and hypoxia becomes a form of environmental stress on the human organism. This is, accordingly, the upper limit for any sort of mining operations. At such high altitudes special precautions must be taken to protect the health of the miners, including mechanization of mine operations, provision of oxygen as needed, reduction in the number of hours worked, and establishment of residences at lower levels.

With our goal of disease prevention in mind, it was possible to separate miners into different groups according to their hemoglobin levels. Here we are concerned with the capacity of five

such groups to live and work at high altitudes. Each group contained individuals with the following hemoglobin levels: Group 1—up to 12.9 g per 100 cc (anemia); Group 2—13.0-15.9 g per 100 cc (compatible with life at or below sea level); Group 3—16.0-20.9 g per 100 cc (compatible with life and work at high altitudes); Group 4—21.0-22.9 g per 100 cc (borderline area, upper limit of hematic compensation); 23.0 g or more per 100 cc (altitude sickness, severe erythremia).

This classification is somewhat arbitrary and the limits established are subject to modification. Nevertheless, in practical terms it is very useful, as it is important that selection of high-altitude miners be based on a classification of this sort.

The frequency curve in Figure 2 shows the hemoglobin levels found in 3,138 miners from five mining centers situated above 4,400 m (22). The mean hemoglobin level was 19.4 g per 100 cc (standard deviation ± 2.2 g). In 0.3 per cent of the cases the hemoglobin value was less than 13 g per 100 cc; 6.5 per cent showed a level between 13 and 16.9 per 100 cc; 70.2 per cent had between 17 and 20 g per 100 cc (adaptation range); 18.3 per cent had levels between 21 and 22.9 g per 100 cc (borderline range) and 4.6 per cent had more than 23 g per 100 cc (altitude erythremia range). Workers with very high hemoglobin levels (in the altitude erythremia range) had a number of special radiologic, cardiographic, and functional respiratory characteristics. Differences between these features and those of well-adjusted high-altitude dwellers are described in the sections that follow.

Radiologic Features

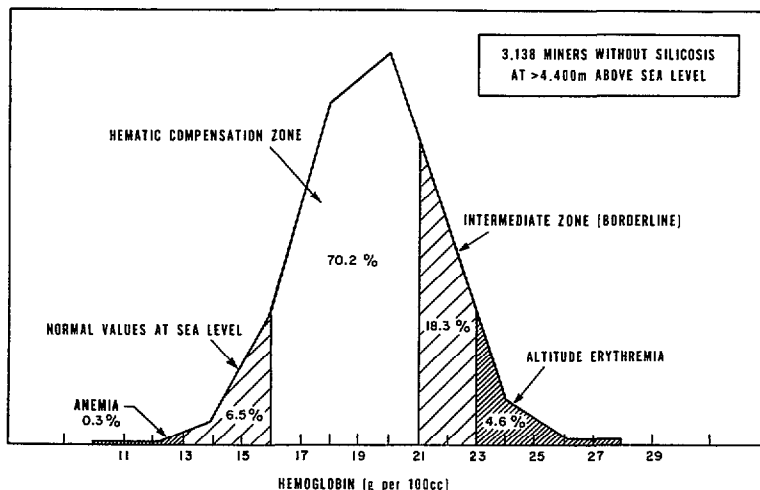
A number of authors have pointed out that high-altitude dwellers have special radiologic characteristics (3, 23). These depend on various factors, including special chest configuration,

an increase in pulmonary blood volume, and some degree of pulmonary hypertension.

Generally speaking, chest X-rays of such persons are characterized by: (a) slight or moderate intensification of the vascular markings; (b) a widening of hilar shadows; (c) intensification of the hilar-basal markings; and (d) enlargement of the heart shadow. As the hemoglobin level rises, these characteristics become increasingly evident, and in cases of high-altitude erythremia (Photo 1) the chest X-ray image becomes very well defined. Such an image shows the following characteristics: (a) marked increase of the vascular markings; (b) pseudonodulation at the intersection or bifurcation of blood vessels; (c) a congestive hilar image; (d) pronounced increase of the bilateral hilar-basal markings; and (e) pronounced enlargement of the heart shadow. This X-ray image is very typical and can be easily diagnosed by physicians who are accustomed to reading X-rays of high-altitude dwellers.

Another type of X-ray image indicates some degree of pulmonary hypertension, with or without erythremia. As pressure in the pulmonary artery increases, the arterial cone becomes more and more prominent, and the pulmonary

FIGURE 2—Distribution curve for hemoglobin levels found in 3,138 workers at five mines above 4,400 meters, showing the physiologic classification which can be used in selecting persons for high-altitude work.



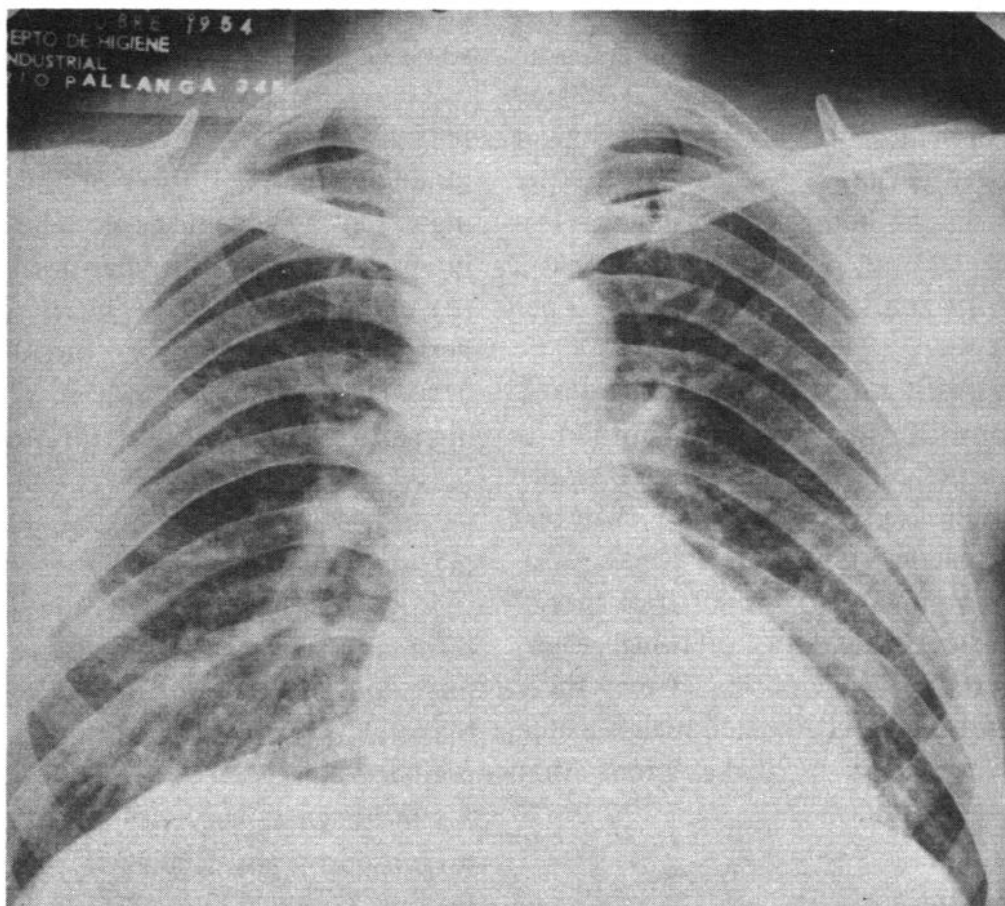


PHOTO 1—X-ray of a worker with altitude erythremia. Note the intensity of the vascular markings with hilar-basal predominance, pseudonodulation in both lung areas, and enlargement of the heart.

vessels serving the lungs' upper and lower lobes become more visible (23).

In cases of severe pulmonary hypertension the X-ray characteristics are also quite specific (Photo 2), including (a) marked prominence of the pulmonary arch (arterial cone); (b) widening of the hilar shadows due to dilatation of the right and left branches of the pulmonary artery; (c) dilation of the pulmonary vessels serving the upper and lower lobes; (d) sinuosity in the intrapulmonary vessels; and (e) diminution of vascularity in the periphery of the lung area. These radiologic features are similar to those described in cases of pulmonary hypertension. Twenty-nine cases exhibiting these features are discussed in reference (23). It should be mentioned that a high incidence of this type of image has been found only at the Volcan Mines center, which is one of the highest in Peru, situated between 4,600 and 5,000 m. In other mines the incidence found has been far lower.

From the radiologic point of view it may be

concluded that Monge's disease manifests itself in three different forms: one is associated with erythremia, hypervolemia, and vascular pulmonary congestion; another is associated with restriction of the vascular bed caused by arteriolar vasoconstriction and resultant pulmonary hypertension; and the third combines these two sets of factors. Existence of pulmonary silicosis in connection with any of these three forms understandably presents complex problems with regard to both clinical and functional diagnosis.

Electrocardiographic Features

High-altitude miners show varying degrees of pulmonary hypertension (14-16), and hence right ventricular hypertrophy, with the latter ranging from mild degrees compatible with life and work at high altitudes to severe ones causing dilation of the pulmonary artery. The

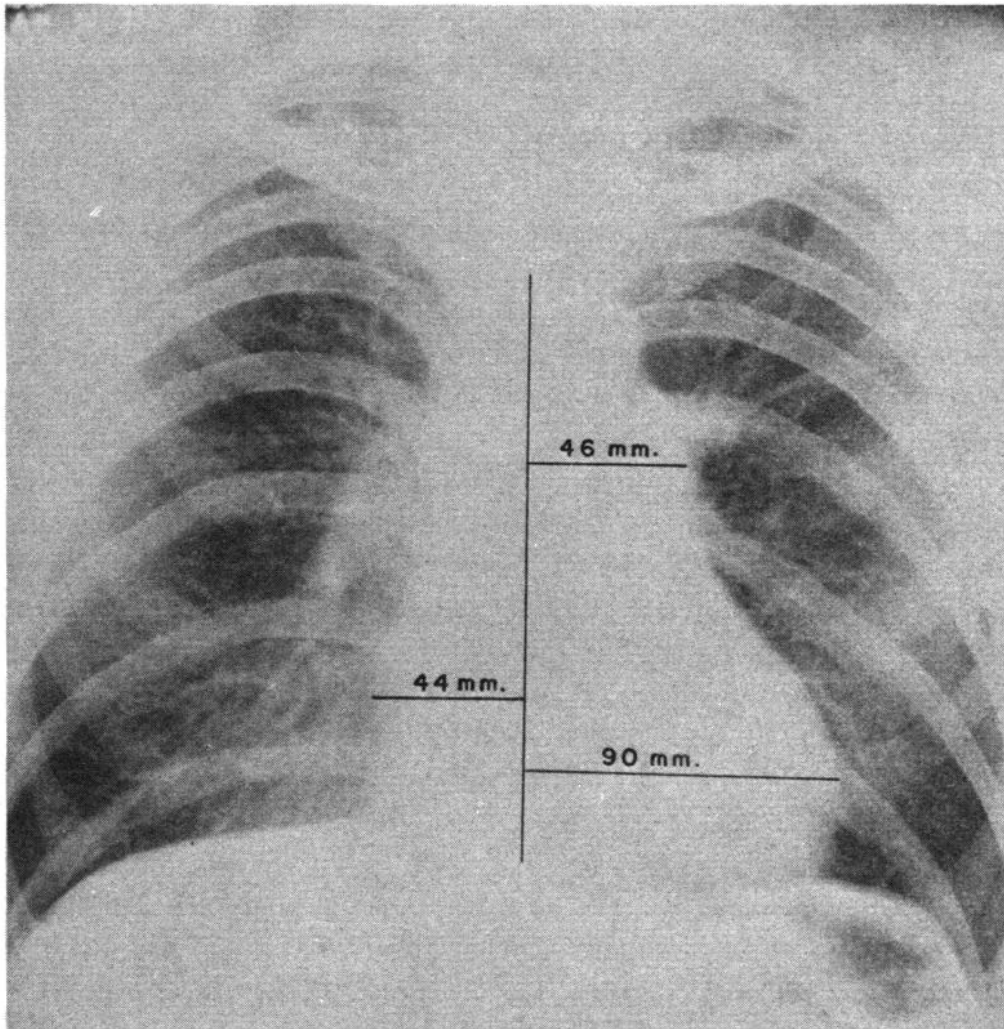


PHOTO 2—X-ray of a worker with a dilated pulmonary artery. Note the intensity of the vascular markings (with hilar-basal and hilar-apical predominance) and the normal-sized heart.

electrocardiograph is among the most sensitive tools for diagnosing right ventricular hypertrophy and, therefore, the degree of pulmonary hypertension.

The electrocardiographic characteristics of normal individuals living at sea level, and at altitudes below 3,500 m, have been described by various authors. Up to 3,500 m these characteristics do not appear to deviate significantly from normal patterns at sea level. On the other hand, electrocardiograms of native workers residing above 4,000 m (9-12) tend to reveal special characteristics. Many show signs of right ventricular hypertrophy and conductive disturbances of the right bundle branch.

Table 2 shows the results of a study of 208 electrocardiograms of miners without pulmonary silicosis working at mining centers situated more than 4,000 meters above sea level (9). The

TABLE 2—Classification of 208 electrocardiograms of apparently healthy workers.

Results of electrocardiogram	Cases	
	Number	%
Normal	108	51.92
Slight or moderate right ventricular hypertrophy	57	27.40
Marked degree of right ventricular hypertrophy	14	6.74
Partial blockage of right branch	28	13.46
Complete blockage of right branch	1	0.48
Total	208	100

electrocardiograms have been separated into five basic groups, according to the configuration of the ventricular (QRS) complex in precordial derivation V₁.

The electrocardiograms of Group 1 show the QRS complex in V_1 to be of a normal (rS) type compatible with life and work at or below sea level. Those of Group 2 have a QRS complex at V_1 in which the R:S ratio in V_1 is equal to or slightly greater than 1:1 (RS), which is compatible with life and work at high altitudes. The QRS complex of Group 3 at V_1 has an R/S ratio far greater than 1:1 (Rs or R), showing an inverted wave at V_1 and even further to the left, as far as V_3 or V_4 . This latter electrocardiogram is typical of severe right hypertrophy (right heart strain) and is incompatible with life and work at high altitudes. The QRS of Group 4 correspond to an incomplete bundle branch block and are compatible with life and work at high altitudes in non-dusty places. In Group 5 the QRS correspond to a complete bundle branch block. This electrocardiogram is incompatible with mining work at high altitudes.

The study referred to (9) found 108 electrocardiograms (51.9 per cent of the high-altitude miners tested) to have normal (Group 1) characteristics. Fifty-seven miners (27.4 per cent) had patterns placing them in Group 2, 14 (6.7 per cent) belonged in Group 3, 28 (13.5 per cent) showed an incomplete right bundle branch block and were placed in Group 4, and one case (0.5 per cent) showed a complete right bundle branch block characteristic of Group 5. The high percentage of right heart strain (6.7 per cent) revealed by this study should be noted.

This classification of electrocardiograms is of great usefulness in selecting high-altitude workers, and also in assessing the degree of incapacity produced by silicosis. It thus provides a tool for preventing indiscriminate selection of miners for underground work that requires considerable effort or involves significant exposure to silica dust. In this way aggravation of pulmona-

ry hypertension as a result of pulmonary silicosis or heavy work can be avoided.

Conclusions

The altitude disease originally described by Monge in 1928 involves two varieties of cardio-pulmonary syndrome. One is characterized by erythremia, hypervolemia, and pulmonary vascular congestion; the other shows a predominance or arteriolar vasoconstriction leading to pulmonary hypertension. As has been seen, both forms have well-defined clinical and functional features. Of course, a third syndrome is often found in which the features of the first two are combined. Recognizing these three forms of Monge's disease is of critical importance in selecting people for high-altitude work.

Permitting mine work by people who are physiologically inadequate leads to poor physical labor, premature incapacitation, and heightened susceptibility to silicosis. When silicosis and Monge's disease are combined, worker incapacitation develops quickly and is extremely severe. (These facts are not yet reflected in Peruvian legislation.)

On the other hand, proper selection enables mines to count on a complement of physiologically efficient workers performing tasks within their capacity.

In general, high-altitude mine workers may be separated into three groups (24): workers suited for any type of labor; those suited for surface work (in working environments without dust); and those ill-suited for any type of high-altitude work (or even residence at high altitudes).

To properly place a person in one of these groups requires careful study of his case history, a thorough clinical examination, detailed analysis of relevant hematic values, pulmonary and cardiovascular X-rays, functional respiratory tests, and an electrocardiogram.

SUMMARY

There is a close relationship between a person's hemoglobin level and the altitudes at

which he can safely live and work. The studies reported here show that miners working at high

altitudes can be divided into three groups according to whether their hemoglobin levels are (1) compatible with residence and work at high altitudes; (2) bordering on incompatibility with such an environment; or (3) excessive, indicating altitude erythremia, and therefore incompatible with residence and work at high altitudes.

From the cardiopulmonary viewpoint, three varieties of altitude sickness can be distin-

guished. One is characterized by severe erythremia, hypervolemia, and pulmonary vascular congestion; another involves severe vasoconstriction of the arteries due to pulmonary hypertension and dilation of the pulmonary artery; and the third is a combination of the first two. Special features associated with each of the three varieties appear in chest X-rays, electrocardiograms, and functional respiratory tests.

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