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STUDIES ON THE ADAPTATION TO HIGH ALTITUDES WITH SPECIAL REFERENCE TO CHANGES IN CARDIOVASCULAR FUNCTIONS

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ABSTRACT

Many physiological functions were examined during 22 days of sojourn at high altitudes (4,200-7,000 m above sea level) on Mt. Aconcagua, Argentina. Parameters measured include heart rate, systolic and diastolic blood pressures, cardiac output and stroke volume calculated by Balke's formula, urinary protein, glucose and pH, RBC and Hb of blood, and muscle strength measured by a hand dynamometer and a pinch-meter. Cardiovascular dynamics judged by those parameters was markedly changed during the first two weeks and tended to be normalized towards the end of the third week of sojourn. Diastolic blood pressure continued to increase until the end of the second week. This increase of diastolic blood pressure may be caused by increased peripheral resistance due to increased blood viscosity, and may add extra work load on the subject's heart. Protein was excreted in urine when the cardiac work was lowered during this period. RBC and Hb did not increase until the third day. Subjective symptoms were also checked and analysed.

It is curious that the unpleasant experiences at high altitudes are not manifest during the first couple of days of sojourn but become increasingly prominent in the following days. Those unpleasant experiences fluctuate in parallel with the change in daily routines of living, namely, they are most manifest during sleep at night and slightest during very moderate exercise in the day-time, although there are seen great individual differences in the degree of symptoms. Physiology of today can offer no satisfactory answer to the reasons why the onset of mountain sickness is delayed for one or two days after exposure to the low barometric pressure and why the symptoms fluctuate in a day. There are supposed to exist numerous factors affecting the onset and degree of mountain sickness. The speed of ascent, the age and bodily

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and psychological fitness of the individuals to the altitudes will be factors involved, as well as the level in metabolism, but the role of those factors must be determined by a more careful analysis of the relation between each symptom and the change in physiological functions. Among those the relation between changes in alveolar gas tension and respiratory adaptive mechanisms has been especially well explored by many investigators, and it has been believed that when the low oxygen tension of the arterial blood has not yet been compensated by an increase of hemoglobin, compensatory cardiovascular mechanisms are needed. In contrast, there seems to have been lettle work made to investigate the cardiovascular adaptive mechanisms at high altitudes. The authors believe that in clarifying the mechanisms of early adaptation to high altitudes and the nature of the symptoms appearing in this early stage of high altitude sojourn attention should be paid mainly to the changes in cardiovascular dynamics as well as to the respiratory adjustments.

The authors had the opportunity to study 14 subjects of the 1965-66 Nagoya University Scientific and Mountaineering Expedition to the Andes by checking both the symptoms and the changes in physiological functions. Some views on the problems above mentioned are described in this paper.

The studies were carried out at the base camp (4,200 m above sea level) of Mt. Aconcagua, Argentina. The average barometric pressure at the base camp was 450 mm Hg. Ambient temperature, however, fluctuated between −10°C in the morning before sun-rise and 18°C in the afternoon with bright sunshine. The subjects were 14 Japanese members of the expedition, who stayed for from 5 to 14 days for preparation at Puente del Inca (2,730 m above sea level) before moving to the base camp by mules in one day. During the total of 22 days of soiourn at high altitudes, many physiological functions were measured. Those include 1) pulse rate, 2) systolic and diastolic blood pressures measured by the ordinary sphygmomanometric method, 3) urinary protein, glucose and pH, 4) red blood cell count and hemoglobin percentage and 5) muscle strength measured by a hand dynamometer and a pinch-meter and by pushing a knob of a small counter. Cardiac output and stroke volume were calculated by the heart rate and blood pressure changes[1]. All subjective symptoms were reported by the subjects throughout their sojourn, when manifested.

RESULTS AND DISCUSSION

Cardiovascular dynamics: Fig. 1 shows heart rate, blood pressure and the cardiac stroke volume and cardiac output calculated by changes in blood pressures and heart rate of five subjects. Cardiovascular dynamics judged by those parameters became markedly changed during the first two weeks of sojourn, but tended to be normalized towards the end of the third week at high altitude. Diastolic blood pressure continued to increase until the end of the second week with no change or a slight increase in systolic blood pressure. The diastolic blood pressure was 10-25 mmHg higher than that of the sea level control. Pulse pressure decreased markedly until the end of the second week. The stroke volume calculated by the formula of Balke[1] ran also characteristically parallel with the pulse pressure. It continued to decrease until the end of the second week. The value of the stroke volume at the end of the second week was 75-80 percent of the sea level control. Heart rate increased, on the contrary, during this period so that the calculated cardiac output increased to 125-140 percent of the sea level value.

In one subject (SA), however, the systolic blood pressure increased markedly with a slight increase of diastolic blood pressure, so that the pulse pressure of this subject remained much higher than that of the others during the sojourn. This subject was the only exception that showed an increased stroke volume throughout the first two weeks. Those results can be interpreted to denote that most of the cardiovascular adjustments occur within the first two weeks and are essentially completed by the end of the third week of exposure to the high altitudes, although the initial decreased level of the cardiovascular dynamics never returned to the value of the sea level control. The same conclusion was proposed by Grollman[2] and Asmussen and Consolazio[3]. An increase of the diastolic blood pressure during high altitudes sojourn was also reported by Siri[4]. The increase of diastolic blood pressure at high altitudes, however, did not agree with the results of other investigators[5][6]. It has been said that hypoxia induces relaxation of the coronary artery[7] and probably of all other major capillary beds, and a decreased diastolic blood pressure at high altitudes may be brought about by relaxation of the peripheral blood vessels[8]. A decrease of peripheral resistance was observed at high altitudes in acclimatized newcomers as well as in natives living permanently. Blood viscosity might become higher after hemopoiesis occurs and increase by cold exposure and by a marked hyperventilation occurring at high altitudes. This increase in blood viscosity may produce extra work load on the heart. As far as the diastolic blood pressure is concerned, the subjects in this investigation did not seem to be well acclimatized to the high altitude. Further study will be necessary to clarify the reasons for this disparity seen between the results obtained in this investigation and of others.

Red blood cell (RBC) and hemoglobin (Hb) in blood (Fig. 2): During the first few days at high altitudes, both RBC and Hb in blood did not increase. They started to increase within 3-4 days after arrival to the altitude and reached plateaus with 5.6×10^6 in mm^3 and 104% respectively. This increase in RBC and Hb did not seem to be the first adaptive changes in the blood of subjects exposed to high altitudes, but it could not be denied that erythropoiesis

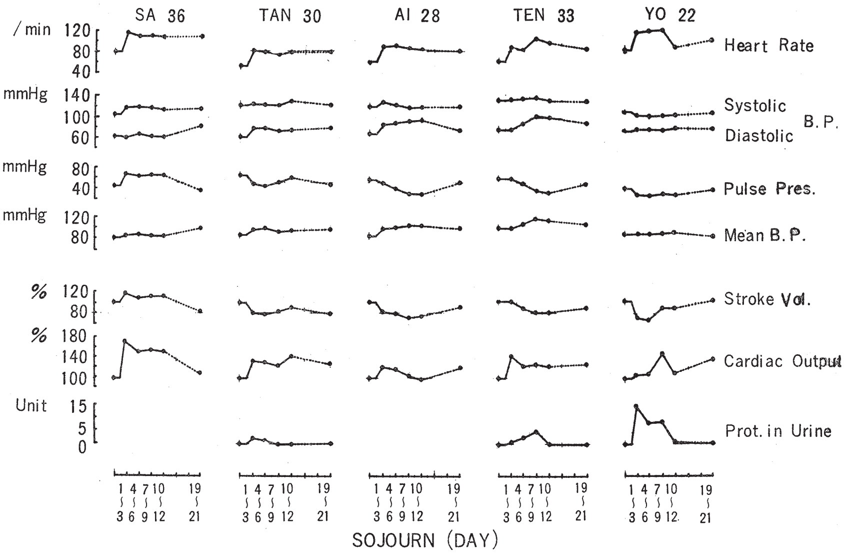

FIG. 1. Heart rate, systolic and diastolic blood pressures, pulse and mean pressures, stroke volume and cardiac output and amount of protein excreted in urine at sea level and at high altitude sojourn of 5 subjects. Values of the latter three parameters are expressed as percentages of the sea level values. Each circle represents mean value for every three days after arrival at 4,200 m altitude, except the results on protein excretion. Protein excreted in urine is expressed in units, as follows, no excreton: 0, slightly positive: 1, 30 mg/dl : 2, 100 mg/dl : 3, 200 mg/dl : 4 and 300 mg / dl : 5, and circles represent total values for every three days.

did not occur by the acute hypoxic stimulation in this early period of sojourn. This no change or slight decrease in RBC could be explained by an increased tendency for destruction of RBC during high altitude sojourn. According to Sumiyoshi *et al.*[9], serum bilirubin was doubled in two days after arrival to a high altitude and this augumentation of bilirubin in blood was caused by an increased destruction of RBC, while RBC has been said to increase in parallel with serum bilirubin concentration[10,11]. Another explanation states that the lowered RBC will be caused by an interaction of two mechanisms, an augumentation of erythropoiesis in bone marrow and an increase of the plasma

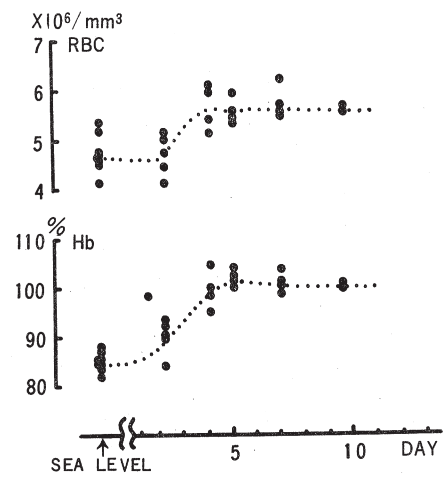

FIG. 2. RBC and Hb at sea level and at high altitude

volume, as has been stated by several investigators[1) 10)]. The average RBC value after it levelled off was much less than that reported by various sources[1) 12)].

Urinary protein (Fig. 1): The amount of protein excreted in urine seemed to run inversely parallel with the decrease in stroke volume and cardiac output. No protein was observed in the urine of subjects after nearly two weeks of sojourn, except for one subject (YO) who ascended to higher altitudes than the base camp. In this subject a very large amount of protein was excreted in urine and marked edema was observed in his face during the first week. He complained of dyspnea and weakness, especially when the cardiac output became lowered in the morning. The appearance of large amounts of protein in urine may be explained by a decreased blood flow through the renal cortex and by disturbance in reabsorption of protein from the renal tubules. Not much change was observed in pH and glucose in urine. Changes in electrolytes and hormones were not examined.

Muscle strength (Fig. 3): It was difficult to say that there occurred a significant change in the grasping power of the hand, the pinching power of

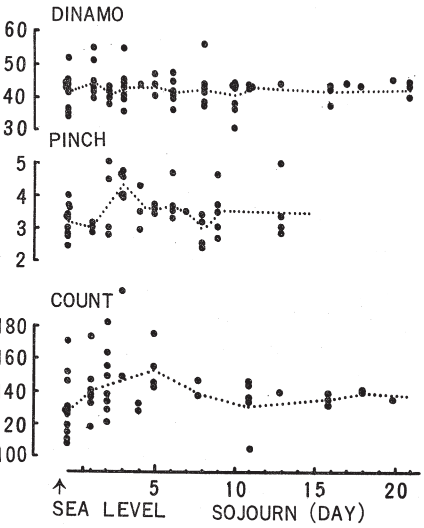

FIG. 3. Changes in muscle strength. Ordinate: Kg for dynamometer and pinch meter measurements. times/30 seconds for counting.

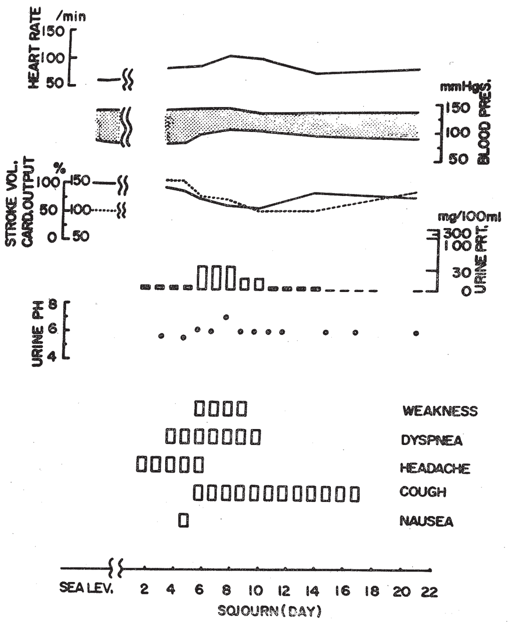

FIG. 4. An example of the changes in cardiovascular dynamics and subjective symptoms expressed as a function of sojourn at high altitude. Subject: TeN.

the fingers and the speed of counting during the 22 days, although the subjects complained of weakness of the muscles. This suggests that subjective weakness of the muscles has no relation to the strength of the muscle twitched for a very short time.

Subjective symptoms (Fig. 4): The symptoms of mountain sickness were experienced, more or less, by all subjects, and of these headache and Chyene Stokes respiration in the early morning were first noted by all subjects. Headache occurred some hours after arrival at the base camp in some subjects, but most did not complain of headache until the next morning. Headache disappeared within one week after the first arrival at the base camp. Weakness and dyspnea with severe cough and sputum appeared much later in many subjects. Those symptoms seemed to be due to decreased activity in function of the cardiovascular system, as the time of onset and duration of those symptoms ran parallel with the changes in cardiovascular dynamics. It is well known that if a subject ascends too rapidly to high altitudes of above 3,600 m he may encounter an important hazard···· acute pulmonary edema. The subjects that complained of severe cough and sputum might have suffered from pulmonary edema during that period. It was evident that all symptoms never appeared at one time in subjects exposed to high altitudes. This suggests that the etiology of each symptom is entirely different. Cough and dyspnea were most severe in the morning. During sleep the heart rate decreased to nearly the sea level control value without an increase in stroke volume. Edema of the face was most evident in the morning. Although the true reasons for the excretion of large amounts of protein in the urine are not clear, it can be partly explained by the reduced circulation in the kidney due to the much lowered cardiac work.

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