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NON-INVASIVE MEASUREMENT OF CIRCULATION TIME USING PULSE OXIMETRY DURING BREATH HOLDING IN CHRONIC HYPOXIA

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Pulse oximetry during breath-holding (BH) in normal residents at high altitude (3510 m) shows a typical graph pattern. Following a deep inspiration to total lung capacity (TLC) and subsequent breath-holding, a fall in oxyhemoglobin saturation (SaO_2) is observed after 16 s. The down-pointed peak in SaO_2 corresponds to the blood circulation time from the alveoli to the finger where the pulse oximeter probe is placed. This simple maneuver corroborates the measurement of circulation time by other methods. This phenomenon is even observed when the subject breathes 88% oxygen (PIO_2 = 403 mmHg for a barometric pressure of 495 mmHg). BH time is, as expected, prolonged under these circumstances. Thus the time delay of blood circulation from pulmonary alveoli to a finger is measured non-invasively. In the present study we used this method to compare the circulation time in 20 healthy male high altitude residents (Group N with a mean hematocrit of 50%) and 17 chronic mountain sickness patients (Group CMS with a mean hematocrit of 69%). In the two study groups, the mean circulation time amounted to 15.94 ±2.57 s (SD) and to 15.66 ±2.74 s, respectively. The minimal difference was not significant. We conclude that the CMS patients adapted their oxygen transport rate to the rise in hematocrit and blood viscosity.

Key words: *breath-holding, circulation, hypoxia, oxyhemoglobin saturation, altitude*

INTRODUCTION

Breath-holding has been studied at sea level by several authors, and the average breath holding time was found to be around 70 s (1, 2, 6-11). This period is extended by breathing a hyperoxic gas mixture (4), hyperventilation, or under

hyperbaric atmospheric air. Breath holding time has also been studied during high altitude ascent, showing a gradual decrease inversely related to high altitude (5, 12). Furthermore, breath holding time has been used to evaluate adequate high altitude adaptation among mountain climbers (5).

Breath-holding, following a deep inspiration to total lung capacity (TLC), in high altitude residents at 3510 m produces a characteristic pattern in the oxyhemoglobin saturation (SaO_2) obtained by finger oximetry (13). The SaO_2, at rest, rises from 91% and reaches maximum values, similar to those at sea level. The time course of a typical breath-holding test is presented in *Fig. 1*. The characteristic saturation pattern reflects the circulation time, which may be used clinically to evaluate cardiac output (14).

The objective of this study was to measure the circulation time, with the use of the saturation curve pattern, in healthy, male altitude residents and to compare it with that in high altitude residents with chronic mountain sickness (CMS). Part of the study has appeared in the abstract form (15)

MATERIAL AND METHODS

The study was performed according to accepted practice concerning safety and ethics of human experimentation, according to the standards and guidelines set by the Declaration of Helsinki. The procedures were approved by a local ethics committee. All study subjects were volunteers who gave informed consent for the study procedures.

The following breath-holding technique was used. The subject, with a nose clip in place, breathed through a mouthpiece and a pneumotachograph for a 2-min control period. The end-tidal carbon dioxide level ($ETCO_2$) was continuously analyzed. A finger probe recorded pulse oximetry.

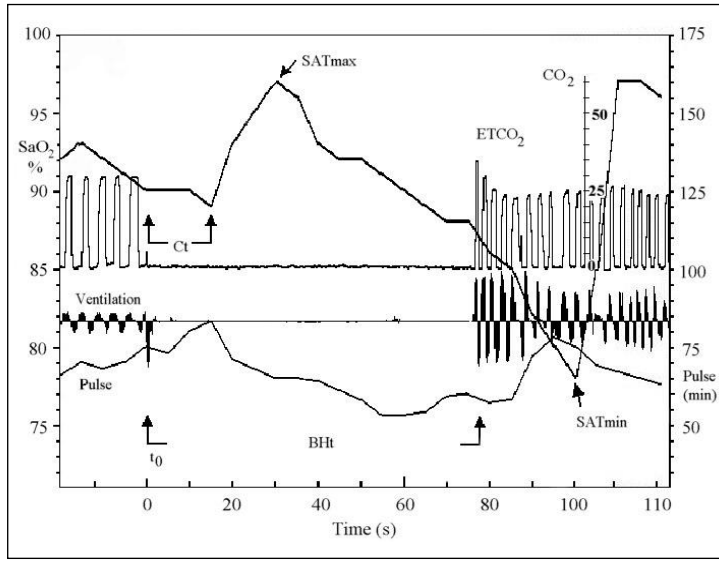

Fig. 1. A typical BH test at high altitude (3510 m) in normal residents. From top to bottom on the left are: SaO_2 from finger pulse oximetry (left ordinate SaO_2 scale in %), $ETCO_2$ (center top right CO_2 scale), integrated curve from pneumotachograph corresponding to ventilation (with no scale), and pulse (right ordinate scale). BHt - breath holding time. Ct - circulation time.

The subject was then asked to take a fast deep breath to TLC immediately after the end of expiration at tidal volume and to hold his breath as long as possible. SaO_2, heart pulse, $ETCO_2$, and ventilation were measured and plotted in real time on the computer screen. Prior to the elevation of saturation to maximum values, a down-pointed peak was observed. The time from the maximum of deep inspiration to the lowest point of this peak is the circulation time from the alveoli to the finger.

The study consisted of 2 groups of subjects. Group N - 20 healthy male high altitude (3100-4100 m) permanent residents (hematocrit <50%) and Group CMS - 17 persons with a hematocrit >58 % (thus classified as having polyerythrocythemia). The latter subjects fulfilled our definition of chronic mountain sickness (CMS) by having one or more underlying disorders. All subjects were non-smokers. Statistical analyses using the Student's *t*-tests were performed.

RESULTS

The results are shown in *Table 1*.

Table 1. Comparison of circulation times in both groups. Group N (Ht <58 %, normal values for 3510 m) and Group CMS (patients with chronic mountain sickness, Ht >58 %).

	Hematocrit (%)	Circulation time (s)
Normal (n=20)	49.7 ±2.57	15.94 ±2.57
CMS (n=17)	68.5 ±6.98	15.66 ±2.74
Statistical significance	P<0.001	Not Significant

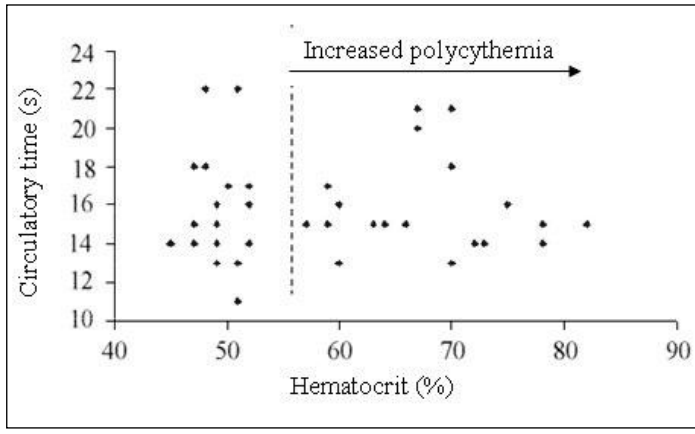

Fig. 2. Relation between hematocrit and circulation time in both groups. No statistical difference was found.

DISCUSSION

Circulation time has been measured through several methods. Clinically, the circulation time is taken as the earliest subjective appearance of an intra-vascular indicator material at a sampling site, usually the tongue or the lung. A wide range of indicators have been used and new ones are being added constantly. Indicators include color, vasodilator effect, radioactivity, effect on respiration,

neuromuscular stimulation, smell, or taste as end points. The substance is injected in the largest vein of an arm and the sensation reported by the subject. If magnesium sulfate is used, a sensation of warmth in the tongue is reported in 7 to 17 s. Ether in saline produces cough in 4 to 8 s and decholin, a bitter taste, in 10 to 16 s in which case the circulation time is inversely proportional to the substance concentration.

There is normal variation in circulation time, when a single indicator is used, depending on whether the arm is raised during injection, on age, sex and central blood volume. There also are variations between methods, the circulation time being 3 s longer with magnesium sulfate than with Evan's blue, as detected by an ear oximeter. All these methods imply the utilization or injection of substances in the organism. Whereas the method described in the present report is unique in the sense that the measurement is made from taking a deep breath and holding the respiration, which is non-invasive and natural. Wexler et al (16), back in 1946, described the use of an oximeter in order to measure circulation time. However, the method used here differs, as it is performed at high altitude and simply following a deep inspiration and immediate breath-holding.

Two possible mechanisms may explain the behavior of the typical BH-curve of saturation changes. Oxygen consumption is increased by a sudden contraction of respiratory muscles, following deep inspiration. At around 16 seconds later, the pulse oximeter in the finger detects a downfall in SaO_2. Fully saturated blood, likewise, would reach the peripheral tissues after the circulation of a "bolus" of a higher alveolar oxygen tension through the arterial system initiated at the lungs and ending in the finger where the pulse oximeter probe is located, again 16 s later. This point corresponds to the SATmax in *Fig. 1*. A sudden deep inspiration to TLC decreases the amount of physiological deadspace ratio to fresh renewed inspired air, raising the alveolar partial oxygen tension (P_AO_2). Another possible mechanism could be an alteration of the pulse oximeter following deep inspiration that would show a momentary downfall of saturation. This could be possible due to circulatory changes as a result of an increase in the negative pressure in the thorax.

Recently, a single breath of nitrogen has been used at sea level, for the measurement of circulation time, as an indirect index of cardiac output, using a Waters fast response oximeter. The lung to finger time was found to be 21.5 s using a normal pulse oximeter and 12.3 s with the Waters fast response oximeter. However, this method differs from ours, since it is performed at sea level and nitrogen is inspired, which includes an initial stage with tidal volume and deadspace filled with a hypoxic mixture. That could produce some delay. Furthermore nitrogen inhalation produces a fall in saturation due to a fall in oxyhemoglobin saturation.

In left ventricular failure and congestive heart failure, circulation time is prolonged. It is usually normal in patients with pulmonary disease who are

dyspneic. In CMS patients, pulmonary disease is frequently present (17, 18) and these patients have typically normal circulation times.

The results of the present study show that there was no statistical difference between the two groups. Although the viscosity of blood is greater in the CMS group, as viscosity increases with increasing hematocrit, that did not slow down the circulation time. Several adaptive mechanisms of CMS allow for efficient transport of oxygen to tissues. The viscosity of blood decreases in vessels with a diameter of less than 0.5 mm - the so-called small diameter or Faahraeus-Lindqvist phenomenon. With increasing blood flow an increasing fraction of red cells is pulled into the axial stream of small vessels, whereby friction is minimized. Red cells function not only as a hemoglobin-oxygen store. Hereby, red cells seem capable of adapting the circulation to the needs of tissues. Also, complex mechanisms that sense changes in O_2 concentration and modulate vascular nitric oxide levels - a central regulator of vascular tone - may contribute (3, 19). The estimation of circulation time presented here cannot be used to distinguish between normality and CMS.

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