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Review

Circulation in the lungs and microcirculation in the alveoli☆

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ABSTRACT

Human lungs weighing *ca* 600 g permit the passage of 5–6 l of blood per minute. The blood capacity of the human lungs is about 0.5 l. Consequently, each 0.5 l of blood is during 5 s. The questions arise of how such a large mass of blood passes through such a small mass of lungs and what the reasons are for such a high rate of blood oxygenation. Since the structure of lungs in mammals is almost the same, we tried to solve these issues studying the rats, in which 20–22 ml of blood pass through the lungs of 1.5–2.0 g mass. A great blood flow appeared to be associated with a large diameter of the lung arterioles and a high rate of the blood flow in them. The high rate of oxygenation is accounted for by a special structure of alveoli and special conditions of the blood flow, which create ideal conditions for oxygen diffusion.

1. Introduction

Energy consumption is a key problem of any living organism. Energy, which is used by the whole animate world of our planet for the immediate maintenance of vital activity and vitality of living tissues is about 1.16×10^{15} kWh per year (Ivanov, 2010). This is almost a 1/1000 part of the energy which the sun gives to our planet. Obtaining the necessary quantity of oxidation energy for the demands of a single organism from the enormous quantity transmitted from sun to earth is a complex and far from single-valued function. This function of delivering oxygen and, consequently, energy is performed by the lungs. In humans and other mammals alike, the mass of the lungs comprises about 0.8% from the body mass. In man, blood flow through 1 g of the lung substance is greater by a factor of 18 than that through 1 g of brain substance (Table 1). In the rat, likewise, blood flow through a unit of lung mass is greater by a factor of 19 than that through a unit of brain mass. Taking into consideration that the brain is one of the best blood supplied organs it is easy to see how the large blood flow passes the lungs. Of great scientific and practical interest is the question of why the blood is relatively quickly saturated with oxygen in the lungs. Nearly 6 l of blood passes the lungs per minute. The blood capacity of the lungs is 0.5 l. Consequently, this quantity of the blood is saturated with oxygen in *ca* 5 s. While performing physical work, the blood flow through the lungs increases by factors of two or three. In such a case, each 0.5 l of blood is saturated almost completely during 2.5–1.7 s. This is a great rate. How can it be explained? The matter is that it is very difficult to make immediate observations of the circulation in the lungs, since a usual optic microscope would not do for this purpose. The light does not make its way through the thickness of the lungs. Purposeful stretching of lung tissue to make the subject of observation thinner immediately arrests the circulation. Up to now it has been completely impossible to study the circulation in the alveoli under physiological conditions and the structure of lung tissue has been studied only in dead lungs. However, the vessel network cannot be seen in dead preparations. It can be seen only upon being filled with the blood. That is why the problems of special features of the structure of blood vessels in the lungs and of circulation in the alveoli under physiological conditions have not been touched upon by the science until recently. The attempts of visualizing the lung function with proton emission tomography, and with other methods known earlier, have all failed under physiological conditions (Harris and Schuster, 2007; Tgavalekos et al., 2005; Galletti and Venegas, 2002; Richard et al., 2002; Mijailovich et al., 1997; Hamvas et al., 1992). A recent work of Tabuchi et al. (2008) performed in the mouse lung with the help of so called 'introvital microscope' is the first interesting attempt to solve this problem. This work shows that there are large microvessels in the lungs. However, the authors failed to determine their number and distribution. Somewhat later, we have found a whole network of large microvessels in the lung and managed to obtain the image of an alveolus under large magnification (Ivanov et al., 2013). The purpose of the present paper was a scrupulous study of life time morphology of the vessel network and of the alveoli. A second purpose consisted in advancing the hypothesis, based on morphological data on the structure of alveoli and physiological data on the blood flow, about specific mechanisms making it possible to increase the rate of oxygen diffusion from alveoli to blood.

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Table 1
Relationships between the quantities of blood flowing through the lungs and brain.

	Brain		Lungs		V (lungs) V (brain)
	Mass (g)	Volume of blood (ml/g/min)	Mass (g)	Volume of the blood (ml/g/min)	
Human	1500	0.53	600	10	18
Rat	~2.5	0.71	1.5	20	19

V – volume of blood.

This function of the alveoli must be important in light of a large mass and large blood flow rate through the mammals' lungs, which hampers the diffusion of oxygen.

2. Materials and methods

We used a special optic device called "contact microscope" to study the structure of the blood vessels in the lungs. The objective of this microscope has the property of illuminating the specimen to be studied. Hence the objective can be in immediate contact with the specimen under study, which enables to see the structure of nontransparent tissues of various organs without external illuminating. The description of this device and of the method of operation with it has been given elsewhere (Ivanov et al., 1985). This present work was carried out on 12 male Wistar rats, weighing 220–250 g. The animals were anesthetized with Nembutal (40 mg/kg, i.p.) and tracheostomized. A polyethylene canula was introduced into the trachea down to the bifurcation. Then, a 4 mm × 5 mm 'window' was made in the thorax. The pleura was incised through this window, which made the lung collapse. The lung was immediately filled with oxygen at a pressure of 20–25 cmH_2O. Through the window, the apical lens of microscope was carefully brought in contact with the lung surface. Then the observations were carried out. The lung filled with oxygen allowed us to make observations in the absence of respiratory movements. The blood motion along the vessels and in the alveoli was video filmed. Separate frames from continuous filming of the moving blood were technically 'snatched out' and used for illustrating the circulation in separate still photographs. A video clip also is supplemented to this article.

3. Results

We observed a completely unusual picture of the lung circulation. In various sites of the lung we saw a powerful circulatory network, consisting of large microvessels about 20–40 μm in diameter. These vessels were located between the alveoli over the whole length of panoramic photographs. They surrounded each alveolus almost on all sides. We emphasize that this network of large vessels is seen only on living preparations, when it is filled with the blood. It is not scanned in dead preparations, damaged, or isolated lungs. Under physiological conditions, the alveoli are arranged in regular rows. We did not see any other sources of blood for the alveoli but this powerful circulatory network, from which all the alveoli receive the blood; the pattern present uniformly in all studied animals. This circulatory network is shown in Fig. 1A.

A thorough morphological study of the network of large microvessels carried out in a living animal, gives an insight into striking details of circulation in the alveoli. In the pictures recorded with the help of a miniature television camera we distinctly saw in the internal and external coatings of alveoli (Fig. 1A and B); precise designations are given in the figure legend. In Fig. 1A the external coating of the alveoli almost unites with the wall of the network vessel, making the gap between them unseen. At a greater magnification (Fig. 1B) these two coatings are seen sufficiently well. The distance between the external and internal coatings is from 2 to 5 μm. The corresponding space is filled with the blood. This is so indeed, since during hypoxia, in still photographs, the blood gets blue not only in large microvessels of the network but also between the external and internal coatings of an alveolus. Much earlier in the 1980s, Weibel (1984, 1989) and West (1985) reported that the blood forms a thinnest layer between assumed internal and external coatings of an alveolus. We substantiated this assumption. The matter is that according to Roughton's calculations a layer of blood only 2–5 μm thick is saturated with oxygen just in several thousandth of a second (Rougton, 1964). Consequently, this abruptly accelerates oxygen diffusion. However, the most important finding of our study was the fact that this thinnest layer of blood is continuously circulating between the coatings. This is clearly seen in the video films. A rapid interchangeability of oxygenated blood owing to this circulation accelerates the diffusion of oxygen even more. Only does this layer of blood take part in the gas exchange between the blood and the air of the alveoli. Rotation of the blood makes possible the use of almost all the area of the internal coating

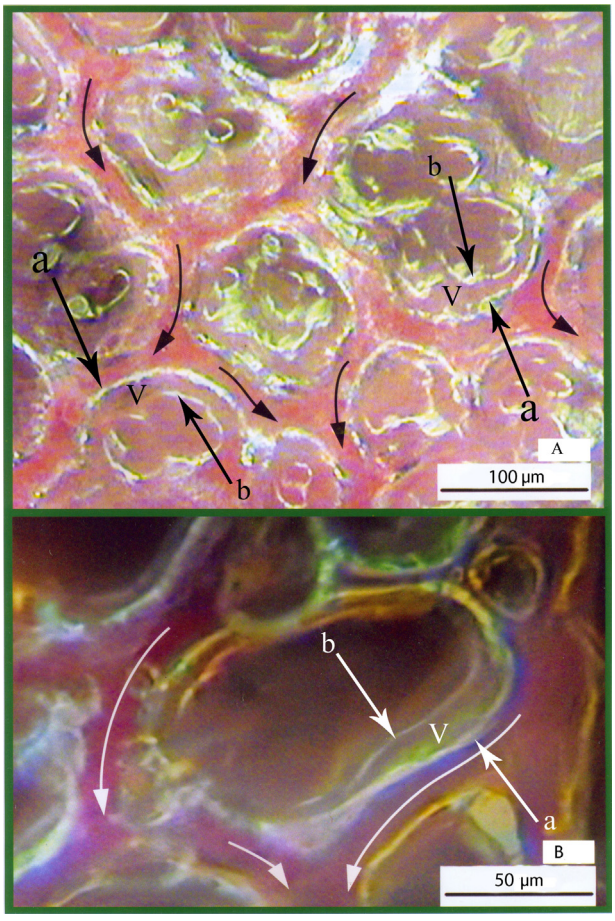

Fig. 1. Panoramic photograph of the blood vessel network and alveoli of the rat. (A) Large microvessels from 20 to 40 μm are seen, which surround separate alveoli. Curved arrows show the direction of the blood flow. Straight arrows point to the coatings of an alveolus: arrows designated 'a' point to the external coatings, arrows designated 'b' point to the internal coatings. The letter 'v' points to the blood between the coatings. (B) Vessels surrounding a single alveolus. Curved arrows show the direction of the blood flow. Markings as above outlined in Panel A.