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PULMONARY CIRCULATION IN EMBOLIC PULMONARY EDEMA

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One of the most threatening complications of pulmonary embolism is edema of the lungs [14]. Publications devoted to the study of the effect of pulmonary embolism on the pulmonary circulation mainly provide discrete data on changes in individual parameters of the pulmonary hemodynamics [10, 12, 14].

The aim of this investigation was to undertake a synchronized study of the blood flow in different parts of the vascular bed of the lungs and also of the pressure in the pulmonary arterial system and left atrium in fat embolism and mechanical embolism of the lungs before the moment of development of pulmonary edema.

EXPERIMENTAL METHOD

The linear and volume blood flow in the left lower lobar artery and vein were studied [8] by an ultrasonic method [5] in acute experiments on 19 cats weighing 3-5 kg, with an open chest and artificial ventilation of the lungs, under pentobarbital anesthesia (30-40 mg/kg, intraperitoneally). The blood pressure in the pulmonary artery was recorded by means of an electromanometer [6]. A cather was introduced through the upper lobar pulmonary artery into the lumen of the left pulmonary artery. The hydraulic resistance of the vascular bed of the lobe of the lung was calculated by means of an analog computer of our own design as the quotient obtained by dividing the mean values of pressure by the mean value of the blood flow in the pulmonary lobar artery. The balance between mean values of the blood flow along the artery and vein was estimated by the same method [9]. The pressure in the pulmonary artery and, in some experiments, in the left atrium also was measured. Three experiments were carried out with a closed chest and natural breathing.

A model of pulmonary embolism was created by intravenous injection of olive oil (1 ml/kg) in the course of 2 min, and a model of mechanical embolism by intravenous injection of a 2.5% suspension of lycopodium (1 ml/kg). All the parameters were recorded for 60-100 min. Repeated injections of oil or lycopodium were given in some of the experiments. The intensity of the developing pulmonary edema was estimated by calculating the pulmonary coefficient (PC) and the dry residue (DR), expressed as percentages [4].

EXPERIMENTAL RESULTS

Edema of the lungs developed regularly after 60 min in both fat and mechanical embolism. This was shown by a significant increase in PC (by 2.1 times for fat embolism, by twice for mechanical) and by reduction of DR (by 20 and 14.8%, respectively). In most animals the intensity of edema of the lungs was greater after injection of olive oil than after injection of lycopodium. Most animals died 60-100 min after induction of edema, four cats died after a shorter interval – varying from 10 to 36 min (after repeated injection of oil or lycopodium).

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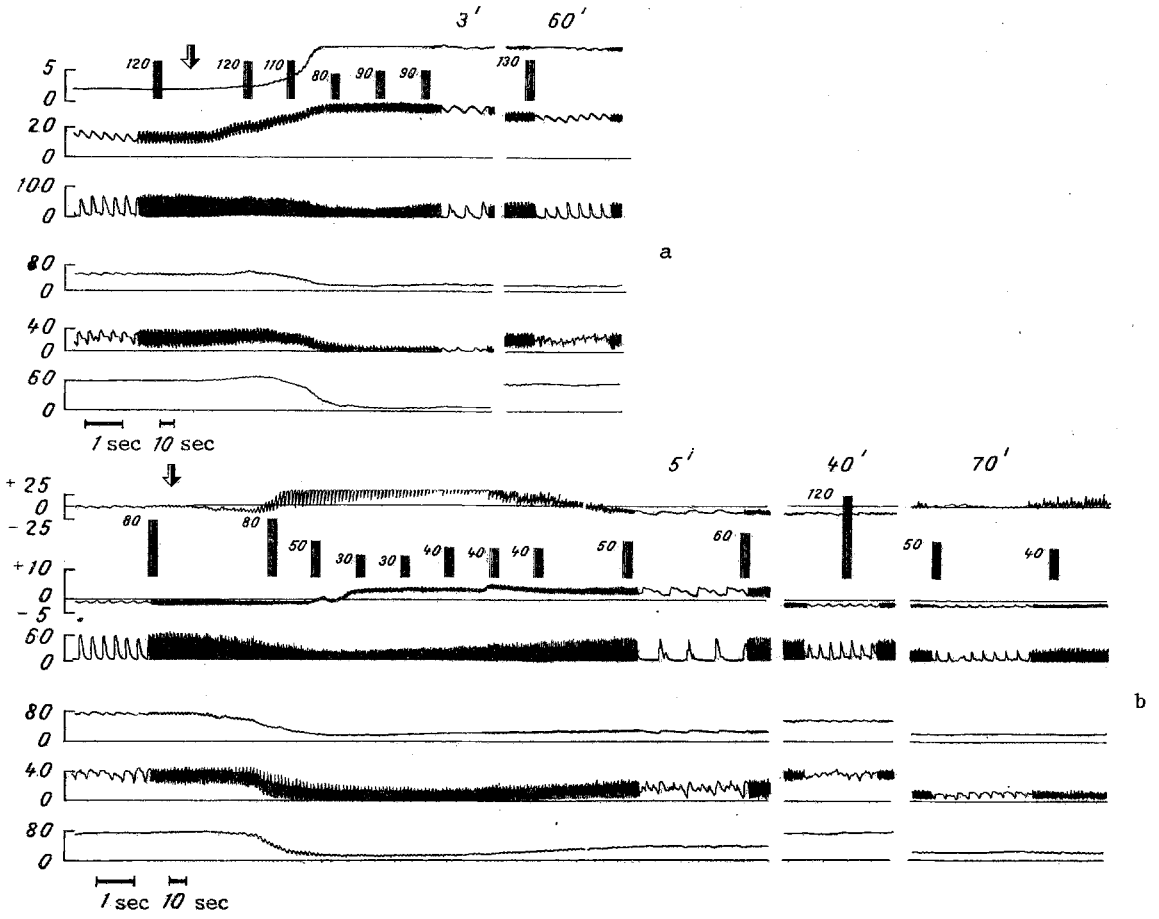

Fig. 1. Changes in parameters of the pulmonary and systemic circulation in fat embolism. Here and in Fig. 2: significance of curves (from top to bottom): a) resistance of lobar vascular bed of lung (in mm Hg/ml/min) and blood pressure in pulmonary artery (in mm Hg), phasic blood flow in lower lobar pulmonary artery (in cm/sec), averaged values of flow in lower lobar pulmonary artery (in ml/min), phasic blood flow in lower lobar pulmonary vein (in cm/sec), average values of flow in lower lobar pulmonary vein (in ml/min); b) balance between blood flow in lower lobar pulmonary artery and vein in relative units (%/%) (upward direction of curve corresponds to increase in blood flow in pulmonary artery relative to blood flow in pulmonary vein, downward direction of curve – increase of blood flow in vein relative to blood flow in artery), pressure in left atrium (in mm Hg), phasic blood flow in lower lobar pulmonary artery (in cm/sec), mean values of flow in lower lobar pulmonary artery (in ml/min), phasic blood flow in lower lobar pulmonary vein (in cm/sec), average values of flow in lower lobar pulmonary vein (in ml/min). Here and in Figs. 2 and 3, thin lines under each curve denote zero levels. Columns represent values of pressure in femoral artery (in mm Hg). Arrow indicates time of injection of olive oil (or lycopodium) into femoral vein. Numbers in top part of figures show time (in min) elapsing after beginning of embolism. Time scale 1 and 10 sec.

During analysis of the results three stages of the process developing after embolism were conventionally distinguished: the primary response to embolism, the period of compensation, and the period of decompensation.

The primary response to embolism usually took the form of a sharp decrease in the linear and volume velocity of the blood flow along the lower lobar artery and vein (Figs. 1a, b; 2b), in individual experiments after a brief increase (Fig. 2a). In most experiments, during the first 6-9 min after both fat and mechanical embolism, the inflow of blood along the artery, although reduced, exceeded the outflow along the vein, i.e., venous congestion of the lungs was present. In some experiments on animals with fat embolism complete cessation of the inflow of blood along the artery was observed, but this was never the case with mechanical

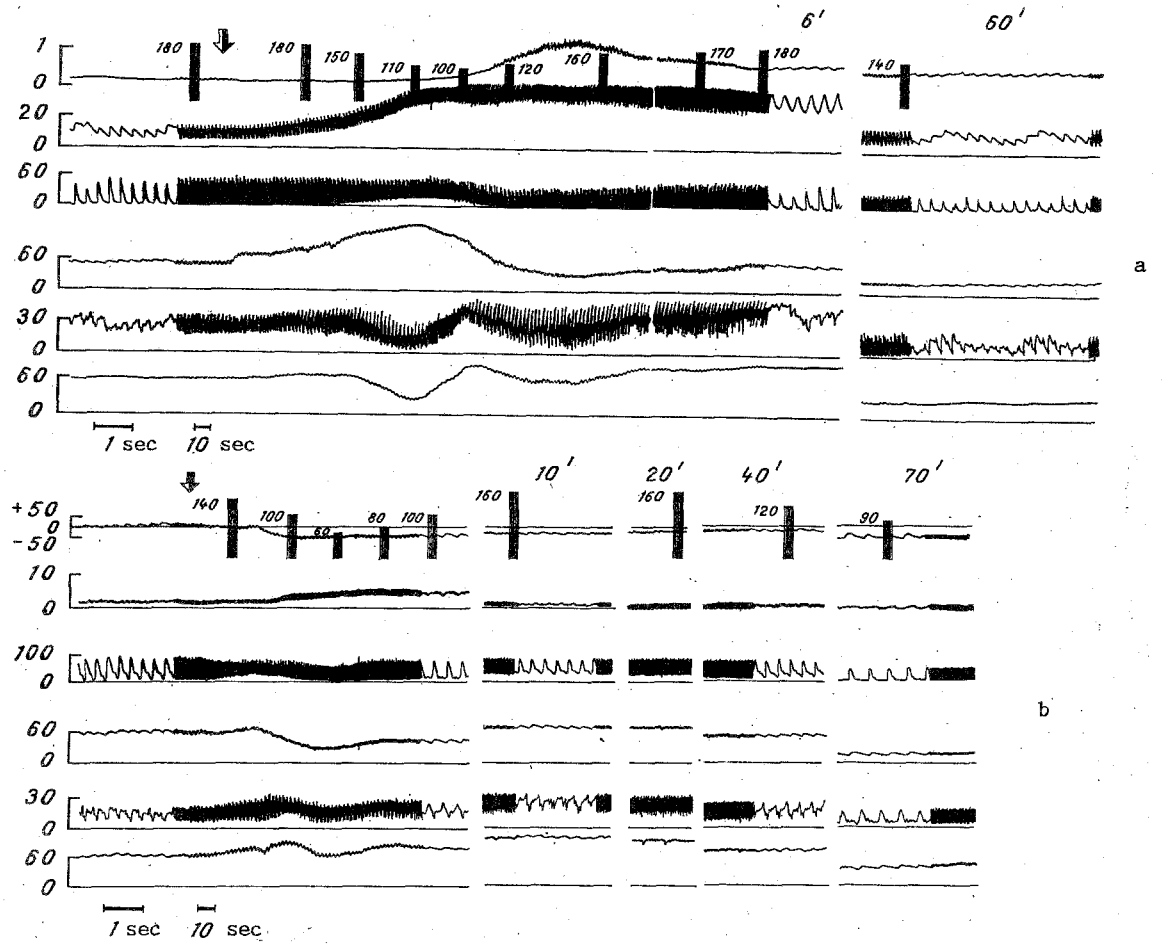

Fig. 2. Changes in parameters of pulmonary and systemic circulation in mechanical embolism.

embolism. In three experiments with mechanical embolism the blood flow in the region studied was increased.

The blood pressure in the pulmonary artery increased in all experiments (by twice in fat embolism, by 2.5 times in mechanical embolism). The vascular resistance of the lungs was increased (Figs. 1a and 2a). It can be concluded from these results that the capillary hydrostatic pressure in the lungs was increased under these conditions [2, 14]. The pressure in the left atrium also rose (Figs. 1b and 2b). After injection of oil or lycopodium the systemic blood pressure (BP) fell sharply during the first 2-6 min – by 50-60% of its initial level. The beginning of the fall of BP coincided in time with the beginning of the response of the pulmonary vessels. In four experiments, however, no sudden response of BP was observed, and the animals died quickly with a progressive fall of BP. In the experiments with an initially low level of BP (below 80 mm Hg) there was likewise no distinct fall of BP in response to embolism. During this period, in animals with fat embolism, marked bradycardia was observed but the cardiac rhythm was not disturbed. In mechanical embolism more marked bradycardia developed (the heart rate was reduced by 50-60%) accompanied by extrasystoles. Besides mechanical obstruction of the vessels of the pulmonary vascular bed, a definite role in the development of the hemodynamic changes in the pulmonary and systemic circulation was played by afferentation from the receptors of the pulmonary vessels and also by the developing hypoxemia [2, 7, 14].

By 10-15 min after the beginning of embolism, the parameters, initially changed, became stabilized and showed partial recovery with the onset of a period of compensation: the initial systemic BP was restored and the heart rate returned to normal (Fig. 2b). However, the pressure in the pulmonary artery and the resistance of the pulmonary vessels remained high (Figs. 1a and 2a), and fell a little only after mechanical embolism. The pressure in the left atrium in the period from 8 to 12 min after injection of lycopodium fell to zero, whereas after injection of oil it became negative (Figs. 1b and 2b).

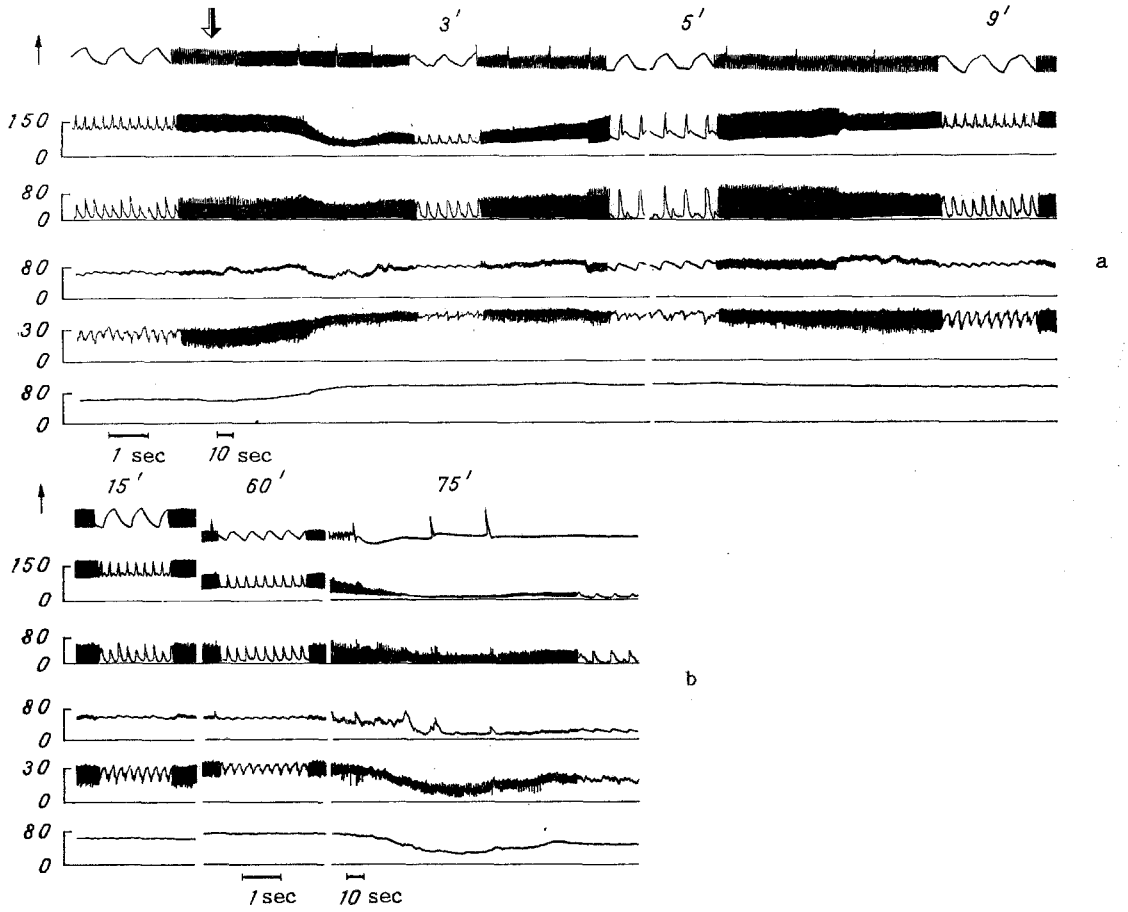

Fig. 3. Changes in parameters of pulmonary and systemic circulation in mechanical embolism (experiment with closed chest and natural breathing). Significance of curve (from top to bottom): a) respiration, blood pressure in femoral artery (in mm Hg), phasic blood flow in lower lobar pulmonary artery (in cm/sec), mean values of flow in lower lobar pulmonary artery (in ml/min), phasic blood flow in lower lobar pulmonary vein (in cm/sec), mean values of flow in lower lobar pulmonary vein (in ml/min); time scale 1 and 10 sec; b) continuation of a.

The velocity of the blood flow along the lower lobar artery and vein gradually increased, but as a rule did not reach its initial level. The writers showed previously that 5-7 min after embolism, fat and lycopodium appeared in the capillaries – i.e., they passed from the large vessels into the microcirculation [3]. This time coincides with beginning of recovery of the blood flow along the large vessels. In this period (sometimes sooner – after 3-5 min) the balance was upset between the inflow of blood along the artery and its outflow along the pulmonary vein; in some experiments the inflow of blood along the artery exceeded its outflow along the vein; in other experiments the opposite was observed: the velocity of the blood flow along the vein exceeded that along the artery. In individual experiments the inflow of blood along the artery was close to zero whereas the blood flow along the pulmonary vein increased. It can be tentatively suggested that this phenomenon is connected with an increase in blood flow along the bronchial arteries: two-thirds of the venous outflow from the bronchial arterial system takes place along the pulmonary veins [2, 11]. There is evidence of a considerable increase in the bronchial blood flow in pulmonary embolism [11]. It has also been shown that the bronchial vessels are an important source of accumulation of liquid in the lungs during edema [1]. It can be postulated that an increase in outflow from the bronchial arterial system during embolism, leading to an increase in the blood flow in the pulmonary vein, masks the true impairment of the outflow from the pulmonary arterial system in those experiments in which values of flow along the pulmonary artery and vein are similar.

Toward the 40th-60th minute a period of decompensation began. Despite the apparent well-being the systemic BP suddenly began to fall progressively, and in the course of 7-10 min it fell from 120-140 min Hg to 40-20-0 (Figs. 1b, 2b, and 3). The velocity of the blood flow

along the pulmonary artery slowed. In the case of mechanical embolism, against the background of a sufficiently high systemic BP level the high velocity of the blood flow along the vein still continued; however, when BP fell to 20-30 mm Hg the blood flow in the vein also decreased (Figs. 1a, b; 2b; 3). These findings are indirect confirmation of the view that an important role in the changes in blood flow along the pulmonary vein in embolism is played by the outflow from the bronchial arterial system.

The blood pressure in the pulmonary artery in mechanical embolism fell a little in the course of the experiment, but still remained higher than initially. In the case of fat embolism the pressure in the pulmonary artery remained high and approached its initial level only in the terminal phase. The resistance of the pulmonary vessels remained high throughout the experiment (Figs. 1a and 2a).

The pressure in the left atrium came close to zero when BP was 30-40 mm Hg, in the terminal phase it become negative, and finally, immediately before cardiac arrest it rose sharply, evidently due to failure of the left ventricle. The heart rate gradually slowed and cardiac arrest supervened (Figs. 1b and 2b). In the closed chest experiments with natural breathing, the cause of death of the animals 60-100 min after the beginning of embolism was respiratory arrest followed by cardiac arrest (Fig. 3).

Analysis of the data indicates that several factors may be involved in the pathogenesis of pulmonary edema associated with embolism. The most important is an increase in the capillary hydrostatic pressure, as indicated by a rise of pressure in the pulmonary artery and left atrium. An important factor is impairment of the outflow of blood from the lungs, which we observed in several experiments, mainly during the transition from the initial response to embolism to the stage of compensation, when the velocity of the blood flow along the pulmonary artery was partly restored and the outflow along the vein was low. In other experiments the parameters of the venous blood flow exceeded those of the arterial, indirect evidence of an increase in outflow of blood from the bronchial arterial system. Depending on the type of embolism, at each stage in its course one of these factors may predominate: taken together they regularly cause the development of some degree of pulmonary edema in the experimental animals.

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