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SCIENCE

Pulmonary Blood Plasma Filtration in Reptiles: A "Wet" Vertebrate Lung?

Warren W. Burggren

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Abstract. *The net loss of plasma from blood into tissues within the ventilated reptile lung is 10 to 20 times greater than that in mammalian lungs. When blood flow is reduced during breathholding by reptiles, the plasma loss stops, and a net reabsorption of fluid from the tissues occurs. Fluid movement dynamics and the relative "dryness" of the lung of reptiles and mammals thus differ in several important respects and reflect the more variable cardiovascular performance of reptiles.*

Fluids continually move in both directions through the walls of blood capillaries. The net hydrostatic pressure (blood pressure) forcing plasma from capillaries is nearly completely opposed by the net colloid osmotic pressure drawing tissue fluid back in, so that net blood plasma loss is very low. In mammalian lungs, only 1 to 4 percent of the blood fluids is lost to the surrounding tissues (*1*), this fluid being effectively drained away by lymphatic vessels. The alveoli (gas sacs) within mammalian lungs thus remain comparatively dry, greatly facilitating diffusion of O_2 and CO_2.

Our current concept of lung fluid balance is based almost entirely on the "dry" mammalian lung, which is constantly perfused at a mean arterial blood pressure of 10 to 15 mmHg (*2*). In reptiles, however, mean pulmonary arterial pressures may be up to five times higher than those in mammals (*3, 4*), because the typical reptilian heart, with its single ventricular pump, produces very similar pulmonary and systemic pressures (*4*). In view of the elevated pulmonary arterial pressure in reptiles, it is paradoxical that the colloid osmotic pressure of reptilian plasma is lower than that of mammals (*5*), and would seem to be far too low to keep the lung dry by effectively counterbalancing plasma filtration from pulmonary capillaries.

The lungs of reptiles thus appear to be perfused under physiological conditions that are incompatible with our current mammalian-based concepts of tissue fluid regulation. This study, in which measurements were made of the net fluid movements between the vascular and nonvascular spaces of the lung of an ectothermic vertebrate, raises the question of whether a dry lung is a trait of all air-breathing vertebrates.

The turtle *Chrysemys (Pseudemys) scripta* was chosen because of its high pulmonary arterial blood pressure (*4*) and the ease of access to its lungs and blood vessels. Extracellular fluid in the lung was assumed to be in one of two compartments—vascular (within blood vessels) or nonvascular (extracellular tissue spaces, alveoli, and lymphatic vessels). Instantaneous net flow of fluid between these two lung compartments was measured with an electromagnetic flow probe and a modification of an indicator dilution method for measuring capillary permeability (*6*). Instead of using an artificial indicator, I based calculations on red blood cell (RBC) concentrations in simultaneously drawn samples of pulmonary arterial and pulmonary venous blood (*7*). For each of eight turtles, four to six paired blood samples (100 μl) for RBC counts were taken within a 24-hour period, during which pulmonary arterial blood pressure and left pulmonary artery flow were monitored continuously (*8*). Values, reported as means ± standard deviation ($N = 40$), for heart rate (24 ± 6 beats per minute), blood pressure (17 ± 6 mmHg) (*9*), and minute blood flow to the left lung (7.38 ± 4.82 ml/kg) were in excellent agreement with reported values (*3, 4*), as were cardiovascular events that occurred during intermittent lung ventilation (Fig. 1).

The concentration of RBC's in pulmonary venous blood was often 10 to 40 percent higher than that in pulmonary arterial blood, a disparity many times greater than is found in rabbit lung vessels (*10*). However, variation was common between pairs of samples, even when taken only 2 minutes apart. These paired RBC counts, as well as lung blood flow at the time of sampling, were used to calculate the net flow and direction of plasma movement in the lung. There was a significant correlation ($r = .78$; $P < .001$) between the rate of plasma filtration and pulmonary blood flow (Fig. 2). At blood flows of 12 to 14 ml/kg-min evident during lung ventilation, 20 to 30 percent of the fluid entering the lung remained behind in the nonvascular lung tissues. However, when blood flow fell to only 2 to 4 ml/kg-min during breathholding, plasma filtration stopped or even reversed, causing reabsorption of fluid from pulmonary nonvascular spaces. There was no significant relation between lung filtration or reabsorption and mean pulmonary arterial pressure, which fluctuated during intermittent breathing (Fig. 1).

The most striking difference between pulmonary filtration dynamics in mammals and reptiles is the apparent "leakiness" of the turtle pulmonary capillaries. When lung blood flow is high during ventilation, the volume of plasma filtrate is approximately 10 to 20 times greater than that in mammalian lungs (*1*). A contributory factor may be the high pulmonary arterial blood pressure of *Chrysemys*, which exceeded mammalian pulmonary arterial pressures by 20 to 40 percent. Capillary blood pressure (which remains to be measured) will be lower, but some proportion of the elevated arterial pressure of *Chrysemys* is almost certainly transmitted to the lung capillaries. Since blood colloid osmotic pressure of turtles is lower than that in mammals (*5*),

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... hydrostatic and colloid osmotic pressures may largely account for the considerable plasma loss from lung capillaries. Reptilian capillaries are relatively permeable to proteins (*11*), and this would also contribute to lung plasma filtration by allowing blood proteins to enter the nonvascular compartment and elevate its colloid osmotic pressure.

A correlation between lung blood flow and transcapillary fluid movement in the vertebrate lung has not previously been described. Three- to 20-fold increases in pulmonary blood flow during breathing are common in reptiles (Fig. 1) and must require a substantial recruitment of unperfused capillaries, as can occur in the fish gill or mammalian lung (*12*). During breathing in *Chrysemys*, there must be a great increase in total capillary wall surface area across which hydrostatic and colloid forces interact to exude plasma from the capillaries.

Fluid reabsorption during breathholding cannot be explained simply by a reduced perfusion of lung capillaries. Reduction of pulmonary flow by arterial vasoconstriction (*4*) may cause a fall in lung capillary pressure sufficient to reverse the net pressures driving plasma from the blood, thus leading to fluid reabsorption. A similar fluid reabsorption and resultant blood dilution occur during interruptions of blood flow in mammalian skeletal muscle (*13*).

Even though lung ventilation and perfusion are intermittent in *Chrysemys*, a very large net plasma filtration prevails. As to how "wet" the turtle lung actually is will depend in part on the unknown effectiveness of lymphatic vessels in removing filtrate from the lungs. However, the widespread concept of the lung as a dry organ may not apply to vertebrates with low colloid osmotic pressures, high pulmonary arterial pressures, and variable blood flow.

WARREN W. BURGGREN

Zoology Department, University of Massachusetts, Amherst 01003

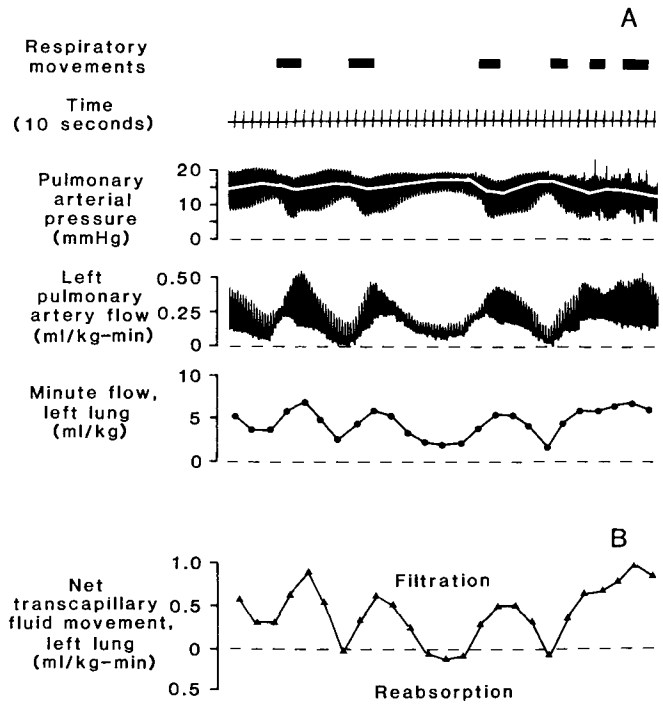

Fig. 1. (A) Pulmonary arterial blood pressure and flow to the left lung of a 1023-g turtle (*Chrysemys scripta*) during normal intermittent breathing. Mean pulmonary pressure is indicated on blood pressure trace by the white line. Lung ventilation is indicated by black bars. (B) Plasma filtration and reabsorption for the period depicted in (A). Calculations were based on data for blood flow and the equation relating pulmonary blood flow and transcapillary fluid movement given in Fig. 2.

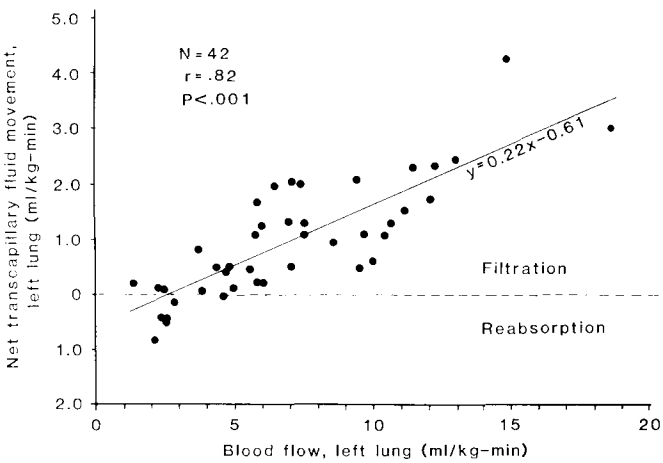

Fig. 2. Relation between the net transcapillary movement of fluid (filtration or reabsorption) and blood flow to the left lung of *Chrysemys scripta*.

References and Notes

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7. Standard indicator dilution methods for determining fluid movement across capillary walls require complex mathematical integration of changing indicator concentrations resulting from single bolus injection. By measuring flow independently and using RBC's as the indicator—the concentration of RBC's ([RBC]) in inflowing pulmonary arterial blood is assumed to remain constant during the 5 to 10 seconds required for blood sampling—the analysis is simplified to

Net transcapillary fluid flow = pulmonary arterial blood flow × $(1 - [RBC]_{pa}/[RBC]_{pv})$

where the subscripts pa and pv refer to the pulmonary artery and pulmonary vein, respectively. Positive values indicate net fluid movement from vascular to nonvascular spaces (filtration), and negative values indicate a net uptake of fluid from extravascular spaces into the blood (reabsorption). The calculations further require the assumption that any change in red blood volume has no significant effect on RBC count (hematocrits and RBC numbers are much lower in *Chrysemys* than in mammals) and that the turtle lung does not sequester and subsequently release significant numbers of RBC.
8. Catheters (PE 50) for pressure measurement and blood sampling were nonocclusively implanted in the left pulmonary artery and left pulmonary vein, while an electromagnetic blood flow transducer was fitted around the left pulmonary artery (*4*). All measurements were made at 22° to 23°C after 8 hours of postoperative recovery.
9. Mean blood pressure for mammals is given by (systolic pressure plus 2 times diastolic pressure) divided by 3. Because of the different elastic properties of the reptilian arteries, mean pressure in *Chrysemys* is best represented by (systolic pressure plus 2 times diastolic pressure) divided by 2.4.
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