EFB 462 Animal Physiology: Environmental & Ecological
Diffusion-based gas exchange: birds' eggs

A bird's egg consists of an embryo contained within a calcareous eggshell permeated by many pores. In the early term, diffusion of respiratory gases through the shell and egg is sufficient to meet respiratory demand, About a third of the way through incubation, however, the embryo's respiratory demands exceed the capacity for diffusion to meet them. At this time, an extra-embryonic membrane, the chorioallantois, begins to develop, and eventually covers the internal surface of the eggshell. The chorioallantois, which is highly vascularized, is homologous to the placenta of the mammalian embryo: it is an external gas exchange. In the mature embryo, then, gas exchange is a coupled diffusion-convection process: diffusion through the pores of the eggshell, followed by convection from the chorioallantois to the embryo. Missing, of course, is the ventilation step in the ventilation-diffusion-convection gas exchange of most animals.

Diffusion gas exchange across the eggshell

Because diffusion is such a slow process compared to convection, exchange of respiratory gases in the bird's egg is essentially a diffusion-driven system, governed by Fick's law:

$$\mathbf{M}_G = \mathcal{D}_G A \alpha (pG_{exh} - pG_v) / x \qquad [1]$$

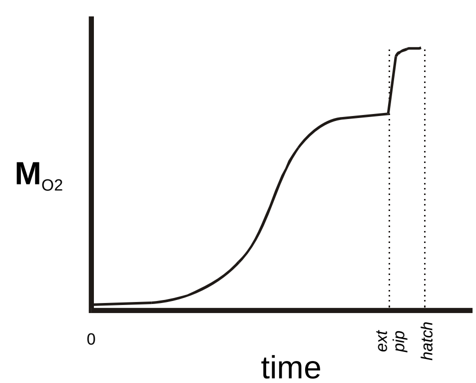
where $\mathcal{D}_G$ = diffusion coefficient, A = the surface area of the gas exchange surface, and x is the thickness of the gas exchange barrier. In the case of a bird's egg, A is equivalent to the summed cross-section area of the pores of the eggshell, A_{pores}, which for the chicken egg is about 70 cm^2. The thickness term x is the thickness of the eggshell itself, x_{shell}, about 0.03 cm, again for the chicken egg. In this analysis, we will consider the diffusion of oxygen, which has a diffusion coefficient in air of about 0.178 $cm^2\ s^{-1}$. So:

$$\mathbf{M}_{o2} = D_{O2} A_{pore} \alpha (pO2_{egg} - pO2_{air}) / x_{shell} \qquad [2]$$

where $pO2_{egg}$ is the partial pressure of oxygen in the air spaces and fluids inside the egg, while $pO2_{air}$ is partial pressure in the atmosphere, which at sea level is about 21 kPa.

Embryonic oxygen consumption

As the embryo matures, its oxygen consumption rates increase. Initially, the increase is quite slow, but as the embryo grows and its growth rate increases, the increase is rapid. Toward the end of incubation, though, the oxygen consumption rate increases at a slower rate, eventually plateauing just prior to hatching. Following the pip of the eggshell, oxygen consumption again increases dramatically.



Limitations on diffusion gas exchange

Because this is a diffusion-driven process, the increased flux of oxygen across the eggshell can be met in only one way: by increasing the partial pressure difference for oxygen across the eggshell. The eggshell experiences no substantial changes in its thickness or pore area through incubation, except when the shell is pipped by the embryo. Similarly, the diffusion coefficient does not change, being a property of how oxygen diffuses through air. Thus, Fick's law lets us estimate how the internal partial pressure of oxygen changes through incubation:

$$pO2_{egg} = pO2_{air} - (\mathbf{M}_{o2}\, x_{shell}) / (D_{O2} A_{pore} \alpha) \qquad [2]$$

The air cell *p*O2 (in black), this mirrors the change of oxygen consumption (in gray). Here we see the real limitation of a strictly diffusion based gas exchanger: it can alter flux rates of respiratory gases only by altering the internal concentrations of gases. In the case of a bird embryo, the decline of internal *p*O2 becomes so severe that it is put into hypoxia, which explains the plateau at the end of incubation. The hypoxia is only relieved by the external pipping of the egg shell, which brings air cell *p*O2 back up to atmospheric *p*O2, enabling the embryo's oxygen consumption rate to again increase.