

COOLING RATES OF LIVING AND KILLED CHICKEN AND QUAIL EGGS IN AIR AND IN HELIUM–OXYGEN GAS MIXTURE

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Abstract—1. In a helium atmosphere, heat is dissipated from a surface 3.5 times faster than it is in air. Eggs in a helium–oxygen atmosphere cool only 1.4 times faster than they cool in air. This signifies that internal resistance to heat flow is a significant factor in the cooling rates of eggs.

2. Heat flow occurs inside an egg in two ways: by conduction through the tissues and in flowing blood. Killing an embryo stops the latter, but not the former. Eggs cool more slowly after they have been killed, signifying that blood flow can be an important component in an egg's internal flows of heat.

3. Blood flow should be a relatively more important component of heat flow in large eggs than in small eggs. The difference in conductance between living and killed eggs is larger in 60 g chicken eggs than it is in 10 g quail eggs.

INTRODUCTION

The heat produced by avian embryos cannot warm their eggs by more than a few °C above air temperature (Romijn and Lokhorst, 1956, 1960; Tazawa and Nakagawa, 1985; Tazawa and Rahn, 1987). Consequently, when an egg is suddenly exposed to a cool environment, its temperature falls in a nearly exponential fashion until it reaches a new, cooler equilibrium.

It has long been known that blood circulation can alter the flows of heat inside a body. A living egg circulates blood within the shell: yet, the embryo's circulation has long been thought not to affect an egg's rate of heat loss, and hence its rate of cooling. Turner (1987) has recently suggested that blood flow could alter an egg's rate of cooling if two conditions are met: (1) the egg must be large and (2) the resistance to heat transfer outside the egg must be small with respect to the egg's internal resistance.

An egg cooling in still air usually does not meet condition (2) above, because air provides a very effective insulating barrier around the egg (Sotherland *et al.*, 1987). Thus, the developing circulation should have little effect on an egg's cooling rate in still air, a supposition confirmed for several species, including chickens (Tazawa and Nakagawa, 1985; Turner, 1987), bobwhite quail (Turner, 1987), herring gulls (Drent, 1973) and ostrich (Turner, unpublished data). However, if the egg's external resistance is lowered, the internal circulation should cause the egg to cool more rapidly as it develops.

Turner (1987) has confirmed this for eggs of chicken and bobwhite quail cooling in still water. This treatment meets condition (2), because an egg cooling in water has an external resistance nearly two orders of magnitude smaller than an egg cooling in air.

A less drastic way to lower the egg's external resistance is to cool the egg in an atmosphere of helium and oxygen. In this paper, we test Turner's (1987) hypothesis by measuring the cooling rates of chicken and quail eggs, cooling in air and in an atmosphere of 21% oxygen and 79% helium.

MATERIALS AND METHODS

Fertile eggs of chickens (*Gallus domesticus*) and Japanese quails (*Coturnix coturnix*) were incubated at 38°C in a forced-draft incubator, where they were turned periodically to ensure adequate gas exchange and development (Tazawa, 1980). We also incubated infertile eggs of both species as controls.

When the chicken eggs were 15 days old, a thermistor probe was inserted 1 cm into the egg through a small hole in the eggshell. The thermistor probe was placed 0.5 cm deep in the quail eggs on day 13 of incubation. The hole was sealed with epoxy cement. For chicken eggs, two additional probes were placed on the eggshell and 1 cm distal to the shell in order to measure steady-state temperature distribution (Fig. 1). The egg, with its probes, was fixed onto a wire frame and placed in a lucite chamber, maintained at 38°C by a water bath (Fig. 1). The thermistor probe was connected to a digital temperature tracer (Takara Therm. Co., Tokyo, model 641), which could measure temperature to a precision of 0.01°C and an accuracy of 0.05°C. The chamber was ventilated with either air or a mixture of 79% helium and 21% oxygen, at a flow rate of 40 ml/min.

The cooling rate of the living egg in air and helium–oxygen was measured first. The embryo was then suffocated, either by stopping the flow of gas through the

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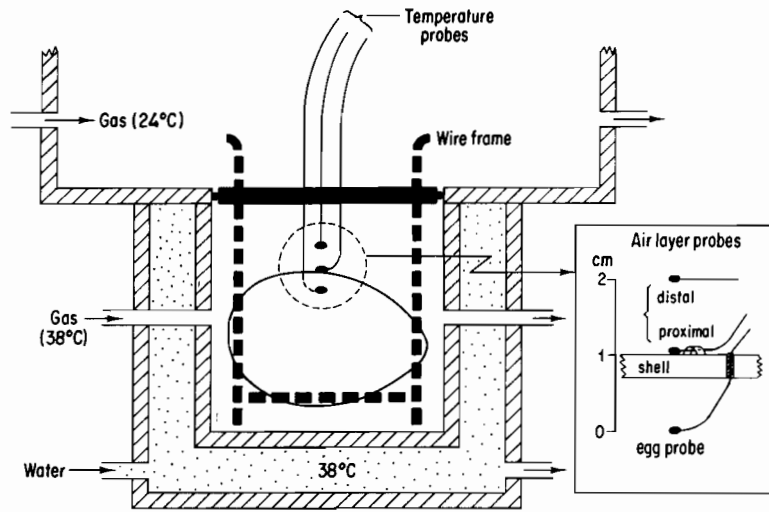


Fig. 1. Schematic diagram of the apparatus used to measure the cooling rates of eggs.

chamber, or by flushing the chamber with pure nitrogen. After the embryo was dead, the cooling rate was measured again.

The eggs were first allowed to equilibrate in air in the part of the chamber maintained at 38°C. The egg and its wire frame were then lifted into the box above, which was maintained at the room temperature of 24°C. Temperature transients were recorded for 5 hr for the chicken eggs and 3 hr for the quail eggs, after which time, the temperature had reached new steady-state (the quasi-equilibrium temperature of Tazawa and Rahn, 1987). The gas mixture was then changed to helium-oxygen, the egg rewarmed and the cooling rate measured again. The embryo was then killed and the series of measurements in air and helium-oxygen repeated. Thus, each egg had its cooling rate measured four times: living, in air and helium-oxygen, and dead, in air and helium-oxygen.

The cooling rate coefficient, k , was approximated by fitting the temperature data to an exponential equation, using the least-square approximation proposed by Marquardt (Awaya, 1983):

$$T(t) = A + B \exp(-kt) \quad (1)$$

where $T(t)$ = egg temperature at any time t , k = cooling rate coefficient (per second), and A and B = constants.

The product of the egg's thermal resistance R (°C/W) and its heat capacitance, C (J/°C), is a time constant, τ ($\tau = RC$, in sec) and its inverse is the cooling rate coefficient ($k = \tau^{-1}$). The egg's heat conductance, G (W/°C), is the inverse of its resistance ($G = R^{-1}$) and is given by the product of the cooling rate coefficient and the egg's heat capacitance:

$$G = kC. \quad (2)$$

If we choose egg density (ρ in g/cm³) and the specific heat (c in J/°C/g) as 1.035 and 3.35, respectively, the heat capacitance ($C = \rho cV$, where V = volume in cm³) of the

60 cm³ chicken egg is 208 J/°C and that of a 10 cm³ quail egg is 34.7 J/°C.

RESULTS

Examples of cooling curves for a chicken and a quail egg are shown in Fig. 2. The curves were approximated by the Marquardt procedure, using Bevington's computer program which was partially modified by Awaya (1983) to derive the best-fitting exponential equation. The cooling rate coefficients for all the cooling curves were evaluated in like manner, and are tabulated in Table 1.

The cooling rates of chicken eggs determined in air agreed well with those previously measured by Tazawa and Nakagawa (1985) for 12–18 day-old embryos. The cooling response of infertile chicken eggs was, however, different from that reported by Kaplan *et al.* (1978) which was much faster than the present values. This might be due to the cable of their thermoprobes which conducted heat from the point of measurement. While it was thick, the diameter of our cable was not more than 1 mm across and the heat conducting through the cable was proved to be negligible by temperature test.

The cooling rate coefficients of quail eggs were larger than those for chicken eggs, as expected from the differences in size and thermal capacitance (Turner, 1985). The cooling rate coefficients in helium were larger than in air, again as expected from the heat transfer properties of helium and air (Table 2). Finally, the cooling rate coefficients were larger for living eggs than for killed or fresh eggs, indicating

Table 1. Cooling rate coefficient ($k \times 10^4$ /sec) for fertile and infertile eggs in air and helium-oxygen (He) atmospheres. Numbers are means \pm SD for $N = 4$

	Fertile					
	Living		Dead		Infertile	
	Air	He	Air	He	Air	He
Chicken	3.60 \pm 0.22	5.02 \pm 0.32	2.91 \pm 0.44	4.03 \pm 0.58	2.44 \pm 0.18	3.28 \pm 0.23
Quail	7.85 \pm 0.81	11.40 \pm 0.83	7.30 \pm 0.62	10.89 \pm 0.62	7.17 \pm 0.34	10.60 \pm 0.68

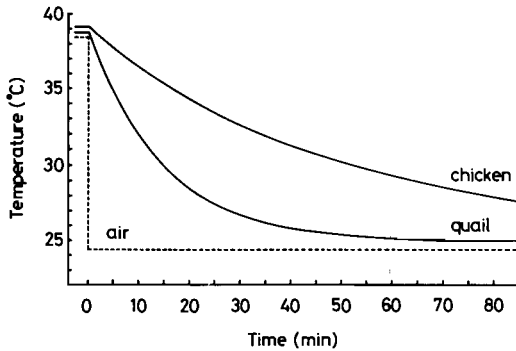


Fig. 2. Temperature traces for representative quail and chicken eggs. For the chicken egg, the equation is $T(t) = 25.54 + 13.58 \exp(-0.0220 t)$. For the quail egg, the equation is $T(t) = 24.90 + 14.05 \exp(-0.0681 t)$. Cooling rate coefficient is given per minute. The dashed line indicates the environmental temperature change.

that living eggs cooled faster than dead or infertile eggs. The difference between living and killed eggs in air was proportionately more for chicken eggs (1.24) than for quail eggs (1.08).

DISCUSSION

One may predict the convection heat loss from the surface of a sphere, if one knows the properties of the surrounding fluid. Comparing helium with air (Table 2), we see that the thermal conductivity of helium is 6.25-fold higher than that of air. However, judging by the respective Grashof numbers (the ratio of buoyant forces to viscous forces), helium is less susceptible than air to the buoyant forces that drive free convection. Consequently, the convective dissipation of heat from eggs should be about 3.5 times faster in helium than it should be in air (Table 2).

However, the proportional difference in cooling rates for eggs in helium and air is smaller—about 1.4 times faster in helium (Table 1). Clearly, there is some factor in addition to heat loss from the surface that governs an egg's rate of heat loss. This other factor is the resistance to heat loss inside the egg. Figure 3 shows the average temperature in the egg, on the shell and 1 cm distal in air and helium-oxygen. In air, the internal resistance of a chicken egg contributes about

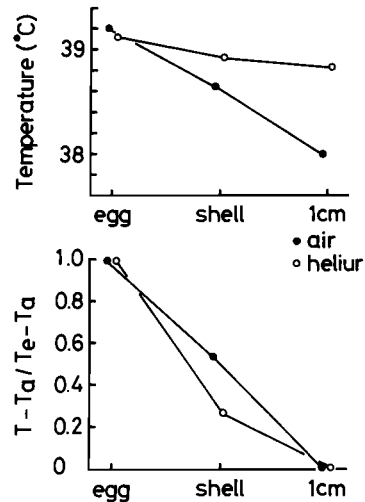


Fig. 3. Steady-state temperature distribution in chicken eggs (average value for four eggs) in atmosphere of air (closed circle) or helium-oxygen (open circle). Top panel: temperatures. Bottom panel: dimension-less temperatures, $(T - T_a)/(T_e - T_a)$, where T_e is egg temperature measured 1 cm inside and T_a , ambient temperature 1 cm distal.

40% of the egg's total resistance, while in helium, it contributes nearly 75%. The internal resistance comprises more than 95% of the egg's total resistance, if it is cooling in water (Turner, 1987).

Therefore, cooling an egg in a helium gas mixture does two things. It makes the egg cool faster than it would in air, being evident from the results (Tables 1 and 2). It also makes an egg's internal flows of heat a more important factor in its overall flows of heat (Fig. 3).

The egg's internal flows of heat are governed by both blood circulation and by the embryo's thermal conductivity. Killing the egg eliminates the contribution of blood flow (and, to a small extent, metabolic heat production; Tazawa *et al.*, 1987), leaving heat to move within the egg only by conduction. The difference in conductance between the living and killed eggs indicates that portion of the egg's total conductance is attributable to blood circulation. Depending upon how important conduction is rela-

Table 2. Thermal properties of eggs in still air and in still helium (He)

	Air	He	He/air
Kinematic viscosity (ν ; m ² /sec)	1.6×10^{-5}	9.6×10^{-5}	5.68
Thermal conductivity (k ; W/m/°C)	0.0262	0.169	6.25
Prandtl number (dimension-less)	0.71	0.71	1.00
Grashof number, chicken egg (dimension-less)	1.5×10^5	4.3×10^3	0.03
Grashof number, quail egg (dimension-less)	3.9×10^3	3.5×10^1	0.01
Convection coefficient, chicken egg (h_c ; W/m ² /°C)	5.2	17.5	3.45
Convection coefficient, quail egg (h_c ; W/m ² /°C)	13.4	50.0	3.70

Table 3. Conductance ($G \times 10^2$; $W/^\circ C$) of living and killed eggs, and their difference (G_{blood}) measured in air and helium-oxygen (He) atmospheres. Numbers are means \pm SD for $N = 4$

	G_{live}		G_{dead}		G_{blood}	
	Air	He	Air	He	Air	He
Chicken	7.55 \pm 0.42	10.48 \pm 0.58	6.09 \pm 0.79	8.41 \pm 1.04	1.46 \pm 0.41	2.07 \pm 0.50
Quail	2.72 \pm 0.24	3.96 \pm 0.25	2.53 \pm 0.18	3.78 \pm 0.19	0.19 \pm 0.10	0.17 \pm 0.08

tive to blood flow, killing the egg (i.e. eliminating the contribution of circulation) will have a greater or lesser effect on its internal flows of heat.

The conduction of heat relative to the transport of heat in blood is large in small eggs, and becomes smaller as eggs get larger (Turner, 1987). In an egg the size of a quail, blood transports about 25% of the heat flowing inside the egg, conduction moving the rest (Turner, 1987). In a chicken egg, the fraction of heat moving in blood rises to 45% and in a very large egg, like the ostrich egg, blood should move about 75% of the heat (Turner, 1987).

It is evident (Table 3) that blood flow is more important for chicken eggs than for quail eggs. The average difference in conductance between living and killed chicken eggs is about 15 $mW/^\circ C$, proportionately about 20% of the conductance of living eggs. For quail eggs, the difference is only about 2 $mW/^\circ C$, a proportional difference of about 7%. Figure 4 shows the proportional contributions of heat flowing through the egg by conduction and by blood flow in chickens and quails.

In brief, blood flow in the egg makes a small, but significant contribution to its thermal conductance.

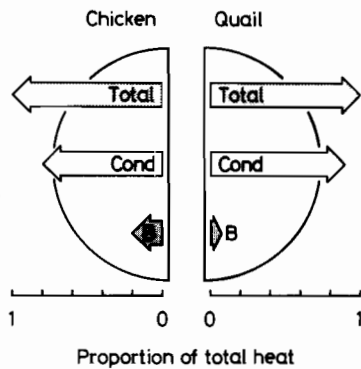


Fig. 4. Proportional contributions of heat flowing through the egg by conduction (Cond) and by blood flow (B) in the chicken and the quail.

This contribution is larger for chicken eggs than it is for smaller quail eggs. The contribution of blood flow is also made more evident by placing the egg in conditions that lower its external resistance.

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REFERENCES

- Awaya T. (1983) *Data Analysis*. Gakkai Shuppan Center, Tokyo, pp. 121–141.
- Drent R. H. (1973) The natural history of incubation. In *The Breeding Biology of Birds* (Edited by Farner D. S.), pp. 262–311. National Academy of Sciences, Washington D.C.
- Kaplan S., Kolesari G. L. and Bair J. P. (1978) Temperature dynamics for the fertile chicken eggs. *Am. J. Physiol.* **234**, R183–R187.
- Romijn C. and Lokhorst W. (1956) The caloric equilibrium of the chicken embryo. *Poult. Sci.* **35**, 829–834.
- Romijn C. and Lokhorst W. (1960) Foetal heat production in the fowl. *J. Physiol.* **150**, 239–249.
- Sotherland P. R., Spotila J. R. and Paganelli C. V. (1987) Avian eggs: Barriers to the exchange of heat and mass. *J. exp. Zool. Suppl.* **1**, 81–86.
- Tazawa H. (1980) Adverse effect of failure to turn the avian egg on the embryo oxygen exchange. *Respir. Physiol.* **41**, 137–142.
- Tazawa H. and Nakagawa S. (1985) Responses of egg temperature, heart rate and blood pressure in the chick embryo to hypothermal stress. *J. comp. Physiol.* **155B**, 193–200.
- Tazawa H. and Rahn H. (1987) Temperature and metabolism of chick embryos and hatchlings after prolonged cooling. *J. exp. Zool. Suppl.* **1**, 105–109.
- Tazawa H., Wakayama H., Turner J. S. and Paganelli C. V. (1988) Metabolic compensation to gradual cooling in developing chick embryos. *Comp. Biochem. Physiol.* (in press).
- Turner J. S. (1985) Cooling rate and size of birds' eggs—a natural isomorphic body. *J. therm. Biol.* **10**, 101–104.
- Turner J. S. (1987) Embryonic blood flow and the heat exchange of avian eggs. Privately published (available on request from the author).