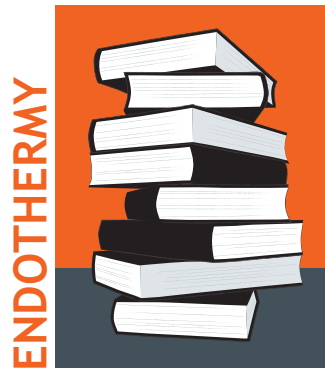


## CLASSICS

## What drove the evolution of endothermy?



Michael Hedrick and Stanley Hillman discuss the impact of Albert Bennett and John Ruben's classic paper 'Endothermy and activity in vertebrates', published in *Science* in 1979.

The metabolic production of heat and high, stable body temperatures characteristic of birds and mammals was a major step in the evolution of vertebrate animals; however, the 1979 paper by Albert Bennett and John Ruben (Bennett and Ruben, 1979) represented a fundamental shift in thinking about the problem of the evolution of endothermy. They argued that endothermy based on thermoregulatory considerations alone (e.g. Bogert, 1949; Cowles, 1958) was not the sole selective advantage for endothermy and perhaps not the initial factor for its evolution. Instead, Bennett and Ruben postulated that the evolution of endothermy was directly linked to the selection for high levels of activity sustained by aerobic metabolism.

Endothermy in vertebrates evolved at least twice in the vertebrate lineage – leading to birds and mammals – along separate, but parallel lines from different groups of reptilian ancestors. The advantages of endothermy are well known: the ability to occupy thermal niches that exclude many ectothermic vertebrates, a high degree of thermal independence from environmental temperature, high muscular power output and sustained levels of activity, to name but a few. Endothermy, however,

is energetically very expensive and requires a great deal of food, compared with the intake of similarly sized ectotherms, to support high metabolic rates.

In their 1979 paper, Bennett and Ruben discussed how high levels of activity and aerobic metabolism could have contributed to the evolution of endothermy. The low-cost metabolic advantages of an ectothermic lifestyle, such as the increased energy to devote to growth and reproduction, led Bennett and Ruben to argue that it is difficult to see how endothermy could have arisen solely for the benefit of thermoregulation. They then detailed how oxygen consumption increases as physical activity increases and pointed out that there appears a 'consistent linkage between resting and maximal levels of oxygen consumption in vertebrates' with a ratio of maximal to rest that is generally between 5 and 10, although they acknowledged that there was too little comparative information available at the time to determine what generally limits maximal metabolism of vertebrates.

Bennett and Ruben then presented how animals with higher aerobic capacity can attain and sustain higher speeds. Endotherms sustain exertions over a wider range of speeds than ectotherms, which resort to anaerobic metabolism to fuel activity at high speeds, and Bennett and Ruben pointed out that 'the ectothermic ancestors of the endothermic groups would likewise have been subject to these behavioural constraints of low stamina'.

After establishing the significance of the increased aerobic scope of endotherms, Bennett and Ruben stated their belief that selection for increased stamina – with the consequent increase in resting metabolism – was a significant factor in the evolution of endothermy. They then listed many additional evolutionary benefits that might accrue from increased stamina, including territory defence and greater foraging capacity, before suggesting that increased aerobic capacity during activity may in turn require the evolution of a relatively high body

temperature. However, they concluded by stating that the benefits of endothermy do not span all measures of performance, pointing out that the ectotherms' increased capacity for anaerobic metabolism provides them with a greater capacity for burst activity, manifested in reptiles that outspurt mammals of similar sizes.

This paper personally shaped for us an ongoing interest in understanding what limits aerobic metabolism of vertebrates from a physiological perspective, starting in the early 1980s at Portland State University when Hillman was an Assistant Professor and Hedrick was a Master's student (e.g. Hillman et al., 1985; Withers and Hillman, 1988; Hedrick et al., 2015). This subsequently led us to a broader level of thinking about how aerobic capacity relates to endurance and dispersal using aerobic capacity and metabolic cost of transport to define physiological vagility, from ecological and evolutionary perspectives (e.g. Hillman et al., 2014). Considering the legacy of Bennett and Ruben's paper, what have we learned subsequently about: (1) limits to aerobic metabolism; (2) the coupling of maximal and resting metabolic rates; and (3) the proportional role of anaerobic metabolism to support activity in endotherms and ectotherms?

Recent evidence suggests that the delivery of oxygen by the cardiovascular system represents the fundamental rate limitation to maximal oxygen consumption and aerobic metabolism in all vertebrates (Hillman et al., 2013; Hedrick et al., 2015). The remaining convective (ventilation) and diffusive (respiratory and mitochondrial) steps in the oxygen cascade appear to have excess capacity and are therefore not limiting. Because the cardiovascular system represents the principal limit to maximal aerobic exercise, then selection might operate on the cardiovascular system to allow increased aerobic capacity in endotherms compared with ectotherms. We recently tested this idea by examining several key cardiovascular variables in groups of ectotherms and endotherms that were measured under conditions of maximal

Classics is an occasional column, featuring historic publications from the literature. These articles, written by modern experts in the field, discuss each classic paper's impact on the field of biology and their own work.

exercise (Hillman and Hedrick, 2015). Our analysis revealed a clear dichotomy in the cardiovascular characteristics between ectotherms and endotherms: endotherms had significantly elevated maximal heart rates, larger hearts relative to body mass and no difference in vascular conductance (Hillman and Hedrick, 2015). These results suggest that major cardiovascular steps in the support of endothermy were the increased rates of blood flow and cardiac power output (achieved by elevated heart rates) and increased arterial blood pressure (achieved by increased relative ventricle mass). The greatly expanded ability of endotherms to deliver oxygen supported the approximate 10-fold increase in maximal oxygen consumption of endotherms relative to ectotherms. This provides a mechanistic explanation for the variation in maximal metabolism delineated by Bennett and Ruben, but not for the coupling of maximal and resting metabolism.

The 1979 paper also influenced our thinking about the coupling of maximal and resting metabolic rates in vertebrates. Bennett and Ruben reasoned that selection operating on physiological factors to increase aerobic capacity and sustained activity would increase resting rates of metabolism as a by-product of the increase in maximal rates of metabolism. This linkage has also been questioned because endothermic heat production arises from increased mitochondrial metabolism in the visceral organs, whereas the increased metabolism associated with activity is a function of the energy used by skeletal muscles to produce work (Farmer, 2000). There is some empirical support for the aerobic capacity model from studies that have demonstrated a positive correlation between resting and maximal rates of metabolism (Bozinovic, 1992; Hayes and Garland, 1995; Dutenhofer and Swanson, 1996; Boily, 2002). The mechanism that explains the link between resting and maximal rates of metabolism is yet to be discovered.

The use of anaerobic energy metabolism and its generation of lactic acid has always been part of the story of why muscles fatigue, which limits endurance. The implication from the Bennett and Ruben paper is that ectothermic vertebrates derive a greater fraction of their total energy from anaerobic contributions compared with endotherms. Recent analyses confirm this implication and indicate that anaerobic metabolism starts to be used in conjunction with aerobic metabolism at between 50 and 70% of  $\dot{V}_{O_{2,max}}$  in all vertebrate classes (see Hedrick et al., 2015). Anaerobic capacity does not seem to vary between vertebrate classes (Hedrick et al., 2015). The proportional contribution of anaerobic metabolism to total energy expended during maximal activity is considerably greater in ectotherms (Bennett and Ruben, 1979), and results from a lower aerobic potential than in endotherms, not an inherent difference in anaerobic capacity.

It appears that Bennett and Ruben were prescient in stressing the importance of sustainable activity as the likely first step in selection for increased aerobic metabolic capacity leading to endothermy rather than a focus on thermoregulation per se. Their work changed our perspective from one that presented thermoregulation as a means in itself to the concept that it may be a side effect of another process: that physiologically maintaining an elevated body temperature requires the production of heat via metabolism. This has led us to the understanding that the subsequent evolutionary step that was necessary to achieve an elevated body temperature via metabolism, rather than behaviour, required selection for increased insulation to retain the heat generated, and that the heat generated is limited by cardiac power output. The shift in thinking from a thermoregulatory perspective to an aerobic capacity argument put forth by Bennett and Ruben helped to spur a line of research into the limits of aerobic metabolism in ectotherms, and this has

come full circle as a means of providing insight into the evolution of endothermy.

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#### References

- Bennett, A. F. and Ruben, J. A.** (1979). Endothermy and activity in vertebrates. *Science* **206**, 649–654.
- Bogert, C. M.** (1949). Thermoregulation in reptiles, a factor in evolution. *Evolution* **3**, 195–211.
- Boily, P.** (2002). Individual variation in metabolic traits of wild nine-banded armadillos (*Dasylops novemcinctus*), and aerobic capacity model. *J. Exp. Biol.* **205**, 3207–3214.
- Bozinovic, F.** (1992). Scaling of basal and maximum metabolic rate in rodents and the aerobic capacity model for the evolution of endothermy. *Physiol. Zool.* **65**, 921–932.
- Cowles, R. B.** (1958). Possible origin of dermal temperature regulation. *Evolution* **12**, 347–357.
- Dutenhofer, M. S. and Swanson, D. L.** (1996). Relationship of basal to summit metabolic rate in passerine birds and the aerobic capacity model for the evolution of endothermy. *Physiol. Zool.* **69**, 1232–1254.
- Farmer, C. G.** (2000). Parental care: the key to understanding endothermy and other convergent features in birds and mammals. *Am. Nat.* **155**, 326–334.
- Hayes, J. P. and Garland, Jr. T.** (1995). The evolution of endothermy: testing the aerobic capacity model. *Evolution* **49**, 836–847.
- Hedrick, M. S., Hancock, T. V. and Hillman, S. S.** (2015). Metabolism at the max: how vertebrate organisms respond to physical activity. *Compr. Physiol.* **5**, 1677–1703.
- Hillman, S. S. and Hedrick, M. S.** (2015). A meta-analysis of in vivo vertebrate cardiac performance: implications for cardiovascular support in the evolution of endothermy. *J. Exp. Biol.* **218**, 1143–1150.
- Hillman, S. S., Withers, P. C., Hedrick, M. S. and Kimmel, P. B.** (1985). The effects of erythrocythemia on blood viscosity, maximal systemic oxygen transport capacity and maximal rates of oxygen consumption in an amphibian. *J. Comp. Physiol. B.* **155**, 577–581.
- Hillman, S. S., Hancock, T. V. and Hedrick, M. S.** (2013). A comparative meta-analysis of maximal aerobic metabolism of vertebrates: Implications for respiratory and cardiovascular limits to gas exchange. *J. Comp. Physiol. B.* **183**, 167–179.
- Hillman, S. S., Drewes, R. C., Hedrick, M. S. and Hancock, T. V.** (2014). Physiological vagility and its relationship to dispersal and neutral genetic heterogeneity in vertebrates. *J. Exp. Biol.* **217**, 3356–3364.
- Withers, P. C. and Hillman, S. S.** (1988). A steady-state model of maximal oxygen and carbon dioxide transport in anuran amphibians. *J. Appl. Physiol.* **64**, 860–868.