Teacher Resource for:

Evidence for mesothermy in dinosaurs

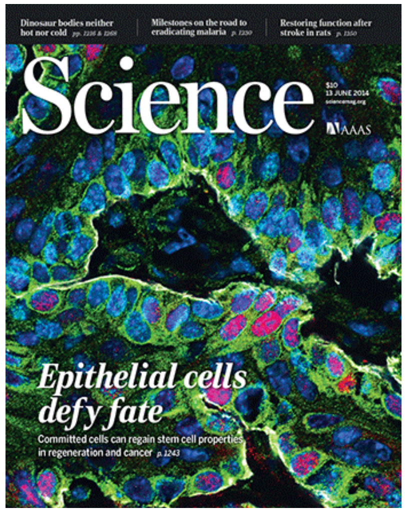

Table of Contents:

NOTE: To explore mass extinctions, including the end of the dinosaurs, we recommend HHMI's free eBook *Mass Extinctions: Lessons from the Past*.

Student Learning Goals

Connections to the nature of science from the article

- Were dinosaurs slow-metabolizing ectotherms like reptiles or fast-metabolizing endotherms like mammals and birds whose activities were unconstrained by temperature?
- How can the resting metabolic rate of extinct species be determined using fossils?

The importance of this scientific research

- This research furthers the understanding of how dinosaurs regulated their body temperature in comparison to known ectotherms and endotherms. It determines the resting metabolic rate of dinosaurs using maximum growth rate as measured by bone growth rings.

The actual science involved

- Thermodynamics
- Paleontology

Connect to Learning Standards:

The Next Generation Science Standards

- Science and Engineering Practice 2: Developing and using models
- Science and Engineering Practice 6: Constructing explanations (for science) and designing solutions (for engineering)

The AP Biology Standards

- Essential knowledge 1.A.4: Biological evolution is supported by scientific evidence from many disciplines, including mathematics.
- Essential knowledge 2.A.1: All living systems require constant input of free energy.
- Essential knowledge 2.C.2: Organisms respond to changes in their external environments.
- Essential knowledge 2.D.2: Homeostatic mechanisms reflect both common ancestry and divergence due to adaptation in different environments.

Common Core English Language Arts

- 11.12.8: Evaluate the hypotheses, data, analyses, and conclusions in a science or technical test, verifying the data when possible and corroborating or challenging conclusions with other sources of information.

Summary of the Article for the Teacher:

It is recommended that this not be used by students in place of reading the article.

General Overview:

Dinosaurs were once thought to be slow, lumber giants with slow ectothermic metabolic rates. More recently, the skeletal structure of some dinosaur bones have lead scientists to conclude that dinosaurs were more agile and faster-growing than once thought. Fast resting metabolic rates (RMRs, a measure of energy expenditure) are typical of endothermic organisms like birds and mammals, which can maintain a constant body temperature higher than the ambient temperature. In contrast, ectotherms, such as amphibians, reptiles, and most fish, have slower RMRs and do not generate enough excess heat from metabolism to maintain a constant body temperature. Whether dinosaurs had energetic systems closer to endotherms or ectotherms is a difficult one to tackle, because the metabolic rate of extinct animals is not directly measurable. However, limited evidence from earlier studies suggests a relationship between the metabolic rate of an organism and its growth rate, which in turn can be determined from fossil bones. So what is this relationship, and how can it help us determine the metabolic rate of extinct species?

The researchers analyzed large, updated data sets on growth rate from both living and extinct vertebrates, using a method that considers body temperature and body size. This enabled the scientists to develop a mathematical model that predicts the relationship between metabolic rate, growth rate, and body size in living vertebrates.

Using these equations and reliable published data on growth rate and body size of dinosaurs, the researchers calculated the RMRs of 21 dinosaur species. The growth rate and age of an extinct animal can be estimated from growth rings in bones that, similarly to tree rings, are laid down annually. Overall bone dimensions, on the other hand, are a great indicator of the animal's size.

The results placed dinosaurs squarely in an intermediate category in between living endotherms and ectotherms, known as "mesothermy." The earliest birds—direct descendants of dinosaurs— plotted as mesotherms, too. Mesotherms, which include living tuna and leatherback turtles, use heat from metabolism to maintain an internal temperature higher than the outside temperature, but they do not "defend" a set temperature.

See also this In Depth feature, which concisely summarizes the findings of the paper: http://science.sciencemag.org/content/344/6189/1216.full

Topics Covered:

- Thermoregulation
- Metabolic rate
- Phylogeny
- Paleontology

Why this research is important:

For several decades, researchers have struggled to determine whether dinosaurs had energetic systems closer to those of rapidly metabolizing mammals and birds, or to those of slower reptiles that do not internally regulate their body temperature. Much of the previous research on this topic has been constrained by a lack of reliable comparative data and the difficulty of estimating metabolic rates of extinct species. Grady and colleagues used a new approach and updated data sets to determine the metabolic rates of 21 dinosaur species, placing them in an intermediate thermoregulation category called "mesothermy." The findings suggest that the current dichotomy of endothermic versus ectothermic may be far too simplistic.

The study can also help us understand the ecological role dinosaurs played in their environment and why they were so successful, ruling Earth nearly uncontested until the asteroid struck. The climate at the time was overall hotter than today, and being a "full" endotherm to be active and fast-growing was not as necessary as in colder climates. In fact, some studies suggest that during the Mesozoic, mammalian endotherms kept their bodies at a lower set temperature than today. So mesothermy may have allowed dinosaurs to grow large and active at relatively low energetic costs compared with endotherms, filling the "large-animal" ecological niche before small, energy-craving endothermic mammals could evolve to become bigger themselves. In addition, being mesothermic probably meant that dinosaurs could easily outcompete the lethargic, ectothermic reptiles.

Methods used in the Research:

- Comparative approach by determining the relationship between maximum growth rate and RMR in extant (living) species
- Ontogenetic growth curve to determine maximum rate of growth
- Mathematical modeling
- Statistic analysis of existing data found in the literature

Conclusions:

- High RMR correlates with fast growth rate. Therefore, an organism's maximum growth rate can be used to predict its resting metabolic growth rate.
- Endotherms have higher RMRs and growth rates, whereas ectotherms have lower RMRs and growth rates.
- Dinosaurs had intermediate growth rates that correspond to intermediate metabolic rates similar to living mesotherms, such as the great white shark, tuna, and leatherback turtle.

Areas of Further Study:

- How can analysis of fossil isotopes, which can shed light on body temperatures, be used to test the hypothesis that dinosaur species exhibited a range of mesothermy?

- Using this method to determine metabolic rates in newborn and juvenile dinosaurs found in seasonally cool environments can give scientists more insight into Mesozoic ecosystems. The technique should be particularly useful in determining the energetic systems of certain groups of dinosaurs (pterosaurs and therapsids) and Mesozoic birds and might provide insights into phylogenetic relationships from a different perspective.

Discussion Questions:

Discussion questions associated with the learning standards

Essential knowledge 1.A.4: Biological evolution is supported by scientific evidence from many disciplines, including mathematics.

- What is the mathematical equation derived by Grady and his colleagues to determine RMR from an organism's maximum growth rate?

Essential knowledge 2.A.1: All living systems require constant input of free energy.

- Compare the food requirements of an endotherm, mesotherm, and ectotherm of the same size.

- Explain why a high RMR would support a fast maximum growth rate.

Essential knowledge 2.C.2: Organisms respond to changes in their external environments.

- Predict what would happen with the metabolic rate of an endotherm, mesotherm, and ectotherm if these animals moved to a cooler environment than they live in now.

Essential knowledge 2.D.2: Homeostatic mechanisms reflect both common ancestry and divergence due to adaptation in different environments.

- How could a mesothermic metabolism have benefited the dinosaurs?

- Which likely evolved first in the ancestors of modern birds: feathers or a high metabolic rate to support endothermy? Provide evidence to support your claim.

- Is endothermy a shared homology between birds (paleognathae) and mammals (placentalia)? Provide evidence to support your claim.

The Science and Engineering Practices contained in the Next Generation Science Standards

Practice 2: Developing and using models

- What information did Grady and colleagues use to develop a way to determine the RMR of dinosaurs?

- Identify the variables the researchers controlled for when selecting data to use to develop the growth rate/RMR model.

Practice 6: Constructing explanations (for science) and designing solutions (for engineering)

- Provide evidence and reasoning for the researchers' claim that "some dinosaurs were mesotherms."

The Common Core English and Language Arts Standards

Integration of Knowledge and Ideas: CCSS.ELA-Literacy.RST.11.12.8: Evaluate the hypotheses, data, analyses, and conclusions in a science or technical test, verifying the data when possible and corroborating or challenging conclusions with other sources of information.

- What conclusions from prior studies did the researchers challenge? What justification do they provide for the validity of their own conclusions?

Discussion questions associated with the figures in the paper

Figure 1

- Across the types (guilds) of thermoregulation, describe the relationship between a species's mass and its maximum growth rate.

- In general, which type of thermoregulation has the highest growth rate at any given body mass?

- According to graph B, dinosaurs had a growth rate most similar to which group of organisms? According graph A, to which thermoregulation type do these organisms belong?

Logarithmic scale graphs

- What is the bottom and top value for each of the following intervals?

  a. 10^0 and 10^2 b. 10^4 and 10^6

- Using graph B, how much greater is the growth rate of a mammal that has an adult mass of 10^8 g versus a mammal that is 10^2 g?

Figure 2

- Compare and contrast mass-independent metabolic rates and growth rates of endotherms versus ectotherms.

- Which two groups of endotherms do not fall on the established theoretical prediction (solid line)?

- Describe why a high metabolic rate would support an endotherm's thermoregulation. (*Hint: Apply the second law of thermodynamics*.)

- Which variable in Figure 2B can be measured in dinosaurs, and how is it measured?

- If an organism had a mass-independent growth rate of 10^{-2} ($g^{1/4}d^{-1}$) what do you predict its mass-independent metabolic rate would be?

- If an organism had a mass-independent growth rate of 10^{-3}, what thermoregulation type would you predict it to be?

Figure 3

- Using Figure 3B, describe the relationship between the mass of a species and its metabolic rate.

- Describe what Figure 3B illustrates regarding the metabolic rates of endotherms, mesotherms, and ectotherms.

- What do you think? How would the amount of food required to support a 10-gram endotherm compare to the amount needed to support a 10-gram ectotherm?

- What is the advantage and disadvantage of being an endotherm versus an ectotherm?

- How was the predicted metabolic rate of the dinosaurs determined?

- How does Figure 3A contribute to the validity of the dinosaur prediction?

- What do you think? How could a mesothermic metabolism have benefited the dinosaurs?

Figure 4

- According to Figure 4, which group of organisms do dinosaurs share a more recent common ancestor with: fish (sharks, groupers, tuna), mammals (placentalia, echidna), reptiles (turtles, crocodiles), or birds (paleognathae)?

- Which likely evolved first in the ancestors of modern birds: feathers or high metabolic rate to support endothermy? Provide evidence to support your claim.

- Is endothermy a shared homology between birds (paleognathae) and mammals (placentalia)? Provide evidence to support your claim.

Multimedia Resources from HHMI's BioInteractive (www.BioInteractive.org)

eBook (iTunes)

Mass Extinctions: Lessons from the Past (https://itunes.apple.com/us/book/mass-extinctions/id1087203609?mt=13). This free book showcases the work of HHMI BioInteractive, including interactive graphics, animations, and videos, designed to examine the evidence and causes of mass extinctions and what we can learn about how humans are affecting the planet.

Short Films and Videos

Great Transitions: The Origin of Birds (http://www.hhmi.org/biointeractive/great-transitions-origin-birds). In the second film of the Great Transitions trilogy, paleontologist Julia Clarke takes us on a journey to uncover the evidence that birds descended from dinosaurs.
Also available as interactive video with embedded quiz:
http://www.hhmi.org/biointeractive/origin-birds-quiz.

The Day the Mesozoic Died (http://www.hhmi.org/biointeractive/day-mesozoic-died). The disappearance of the dinosaurs at the end of the Cretaceous period posed one of the greatest, long-standing scientific mysteries. This three-act film tells the story of the extraordinary detective work that solved it.
Also available as interactive video with embedded quiz:
http://www.hhmi.org/biointeractive/mesozoic-film-quiz.

Scientist at Work: How To Find a Dinosaur (http://www.hhmi.org/biointeractive/how-find-dinosaur). Paleontologist Tyler Lyson describes dinosaur digs and his focus on prehistoric turtle fossils.

Feature Film

Mass Extinctions: Life at the Brink (http://www.hhmi.org/biointeractive/mass-extinction-life-brink and http://www.smithsonianchannel.com/shows/mass-extinction-life-at-the-brink/0/3413789). Mass extinctions have ocurred at least five times in the past, and some experts believe a manmade mass extinction could be next. Is our planet in trouble? And if so, is there anything we can do to stop the sixth mass extinction? Experts are traveling the world, performing groundbreaking scientific detective work to answer these very questions.

Collection

Extinctions (http://www.hhmi.org/biointeractive/explore-extinctions). A variety of engaging videos, films, lectures, online interactives, posters, and classroom activities to teach key concepts related to extinctions past and present.

Online Interactives

Mass Extinctions Interactive (http://www.hhmi.org/biointeractive/mass-extinctions-interactive). Discover the environmental factors that caused the five big mass extinctions in Earth's history and which species they impacted. *Also available as poster:* **The Making of Mass Extinctions** http://www.hhmi.org/biointeractive/making-mass-extinctions

Comparative Anatomy of the Domestic Chicken
(http://www.hhmi.org/biointeractive/comparative-anatomy-domestic-chicken). Trace the

evolutionary history of birds by comparing the shapes and structures of certain bones in a chicken to those of some of its extinct and living relatives.

Image of the Week

Your Turkey's Ancestors (http://www.hhmi.org/biointeractive/your-turkey-s-ancestors). A reconstruction of *Anchiornis huxleyi*, a feathered dinosaur that is part of the ancestral lineage of birds.

Classroom Activities

How Did Dinosaurs Regulate Their Body Temperature?
(http://www.hhmi.org/biointeractive/how-did-dinosaurs-regulate-their-body-temperature). This activity uses data from Grady et al. (2014) to explore thermoregulation in living and extinct animals, including dinosaurs. Students learn about the methods used to determine the metabolic rates of these animals, and they will analyze, interpret, and graph scientific data.

Living Dinosaurs: Fact or Fiction? (http://www.hhmi.org/biointeractive/living-dinosaurs-fact-or-fiction). Students evaluate and discuss statements about the evolutionary relationship between birds and dinosaurs and other facts about these groups, before and after watching the short film Great Transitions: The Origin of Birds.