

- 5.4 ± 0.2; Northern Hemisphere, 5.5 ± 0.1; Southern Hemisphere, 5.6 ± 0.1; globe, 5.5 ± 0.1. The e-fold times for SPO and PSA are based on fewer data than for the other sites (2). The uncertainties quoted on the global e-fold time (1 SD) include a statistical uncertainty in determining the decay exponent and the potential influence of drift in calibration reference standards and detector nonlinearity. See (2) for additional discussion of this and other uncertainties. Provided that the OH-CH<sub>3</sub>CCl<sub>3</sub> reaction rate constant and the loss rates of methyl chloroform to the ocean and stratosphere are known (14–16), the observed global e-fold time defines a lower limit of 1.0 (±0.2) × 10<sup>6</sup> rad cm<sup>-3</sup> to mean OH in the global troposphere (22) and upper limits to the global lifetimes of other important reduced gases such as CH<sub>4</sub>, hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) that are entirely independent of calibration accuracy and emission figures for CH<sub>3</sub>CCl<sub>3</sub> (2).
18. Consumption (that is, sales leading to emissions) of CH<sub>3</sub>CCl<sub>3</sub> in the Northern Hemisphere during 1995–1998 accounted for 90 to 95% of global consumption (20). Here we assume that this ratio is relevant for the distribution of emissions as well. Data contained in these reports (19, 20) have been combined to provide global estimates of emissions through 1998 and projections for likely emissions in 1999 (A. McCulloch, personal communication, 1999). Global emissions of 30 (<40) Gg in 1997, 16 (<24) Gg in 1998, and 13 (<20) Gg in 1999 are calculated from this analysis (numbers in parentheses represent upper limits determined by A. McCulloch after considering accelerated release and higher total production in recent years).
  19. P. M. Midgley and A. McCulloch, *Atmos. Environ.* **29**, 1601 (1995).
  20. *Production and Consumption of Ozone-Depleting Substances 1986–1998* (United Nations Environment Programme, Nairobi, Kenya, 1999), table 5 (available at [www.unep.org/ozone/DataReport99.htm](http://www.unep.org/ozone/DataReport99.htm)).
  21. The stated uncertainty (1 SD) in the estimated global and Southern Hemispheric lifetimes includes global emissions of 15 (+17, -8) Gg year<sup>-1</sup> in 1998–1999, ±30% in absolute measurement calibration, and the uncertainties discussed in (2) and (17). The Southern Hemispheric lifetime estimate also includes an additional uncertainty associated with the time it takes for air to exchange between the hemispheres (1/k<sub>ex</sub> = 1.1 ± 0.3 years) and in the mean hemispheric difference during 1998–1999 of 2.9 ± 0.4% (2). The upper limit for emissions used here is larger than suggested in (18) to account for the possibility that small amounts of CH<sub>3</sub>CCl<sub>3</sub> may be emitted from biomass burning (37). Initial upper limits to this emission (37) have since been revised downward and suggest that emissions from burning are probably <10 Gg year<sup>-1</sup> (32). Even smaller emissions (<1 Gg year<sup>-1</sup>) can be inferred from emission ratios for CH<sub>3</sub>CCl<sub>3</sub> relative to CH<sub>3</sub>Cl from burning of grasslands and woods in northern Australia (33).
  22. Global tropospheric OH concentrations are calculated here from global lifetime estimates for CH<sub>3</sub>CCl<sub>3</sub>; the rate constant between OH and CH<sub>3</sub>CCl<sub>3</sub>, evaluated at 270 K (8); a partial lifetime for CH<sub>3</sub>CCl<sub>3</sub> with respect to oceanic loss of 94 years (15, 16) and with respect to stratospheric loss of 45 years (14); and by presuming that the fraction of atmospheric mass in the troposphere is 0.82 ± 0.02. Uncertainties on OH mixing ratios given in the text and in (17) include uncertainties in the measured decay rate and in the rate constant between OH and CH<sub>3</sub>CCl<sub>3</sub>.
  23. Emissions inferred from our atmospheric measurements and a lifetime of ≤4.8 years are ≥80 to 90 Gg in 1997, ≥42 to 46 Gg in 1998, and ≥35 to 38 Gg in 1999, or nearly three times more than emissions derived from industrial data (18).
  24. P. Jöckel, M. G. Lawrence, C. A. M. Brenninkmeijer, *J. Geophys. Res.* **104**, 11733 (1999).
  25. S. Houweling, F. Dentener, J. Lelieveld, *J. Geophys. Res.* **103**, 10673 (1998).
  26. Y. Wang, J. A. Logan, D. J. Jacob, *J. Geophys. Res.* **103**, 10757 (1998).
  27. X. Tie et al., *J. Geophys. Res.* **97**, 20751 (1992).
  28. M. L. Gupta, R. J. Cicerone, D. R. Blake, F. S. Rowland, I. S. A. Isaksen, *J. Geophys. Res.* **103**, 28219 (1998).
  29. C. M. Spivakovsky et al., *J. Geophys. Res.* **95**, 18441 (1990).
  30. The ratio ⟨OH⟩<sub>n</sub>/⟨OH⟩<sub>s</sub> inferred from trace gas measurements is relevant for hemispheres divided at the natural mixing boundary, the ITCZ. In models, asymmetry in hemispheric OH is often calculated relative to the hemispheres divided at the equator. This difference is significant and must be considered when comparing estimates of ⟨OH⟩<sub>n</sub>/⟨OH⟩<sub>s</sub>. For example, in the model described in (8), ⟨OH⟩<sub>n</sub>/⟨OH⟩<sub>s</sub> = 1.00 when the boundary between the hemispheres is set at the equator; this ratio decreases to 0.87 when the Southern Hemisphere is defined as 8°N to 90°S (that is, when one additional model segment, 0° to 8°N, is included as being part of the Southern Hemisphere).
  31. J. Rudolph, A. Khedim, R. Koppmann, B. Bonsang, *J. Atmos. Chem.* **22**, 67 (1995).
  32. J. Rudolph, personal communication.
  33. D. Blake, personal communication.
  34. We are indebted to all personnel involved in collecting flask samples at the NOAA/Climate Monitoring and Diagnostics Laboratory (NOAA/CMDL) Observatories and at cooperative sampling sites. S.A.M. acknowledges J. Rudolph for suggesting the approach for determining a Southern Hemispheric lifetime and appreciates insightful discussions with A. Ravishankara, J. Rodriguez, M. Prather, S. Solomon, and S. Yvon-Lewis; the helpful comments of anonymous referees; and the technical assistance of A. Clarke, R. Myers, T. Conway, P. Lang, and N. Paynter. Samples were obtained from PSA with assistance from NOAA's Carbon Cycle group. Supported in part by the Atmospheric Chemistry project of the NOAA Climate and Global Change Program. C.M.S. acknowledges the support of NSF through grants NSF-ATM-9320778 and NSF-ATM-9903529.

7 December 1999; accepted 10 March 2000

## Cardiovascular Evidence for an Intermediate or Higher Metabolic Rate in an Ornithischian Dinosaur

Paul E. Fisher,<sup>1\*</sup> Dale A. Russell,<sup>2</sup>

Michael K. Stoskopf,<sup>3</sup> Reese E. Barrick,<sup>4</sup> Michael Hammer,<sup>5</sup>  
Andrew A. Kuzmitch<sup>6</sup>

Computerized tomography scans of a ferruginous concretion within the chest region of an ornithischian dinosaur reveal structures that are suggestive of a four-chambered heart and a single systemic aorta. The apparently derived condition of the cardiovascular system in turn suggests the existence of intermediate-to-high metabolic rates among dinosaurs.

The three-chambered heart of modern reptiles (except crocodiles) includes a single ventricle that pumps blood both to the lungs and to the remainder of the body. In crocodiles, the ventricle is composed of two chambers that are incompletely separated from each other functionally by the foramen of Panazzi. Thus, in all living reptiles, oxygenated blood from the lungs and deoxygenated blood from the rest of the body mix together to a greater or lesser extent, reducing the overall oxygen content of blood returned to the body. All modern reptiles have

paired systemic aortas arising from the ventricle and distributing blood to the body. In contrast, the four-chambered heart of modern birds and mammals has two completely separated ventricles and a single systemic aorta, ensuring that only completely oxygenated blood is distributed to the body. These modifications to the cardiovascular systems of birds and mammals have been correlated with metabolic rates that are higher than those occurring in living reptiles with their incompletely separated cardiac circulation (1).

Much of the discussion about higher metabolic rates in dinosaurs has been focused on saurischian dinosaurs and their role in the origin of birds (1–3). This has been further stimulated by the recent discovery of hair- or featherlike structures preserved with small theropod (saurischian) skeletons from Cretaceous lake deposits in China (3). Ornithischian dinosaurs lack the specializations of some small theropods that suggest high metabolic rates, including enlarged endocranial cavities and complex air-sac systems (1). However, by Cretaceous time, complex dental batteries had appeared in two diversified lineages of ornithischians (ornithomorphs and ceratopsians) (4), suggesting a metabolic need to rapidly digest food. Heat flow indicative

<sup>1</sup>Biomedical Imaging Facility, College of Veterinary Medicine, North Carolina State University, 4700 Hillsborough Street, Raleigh, NC 27606, USA. <sup>2</sup>North Carolina State Museum of Natural Sciences and Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA. <sup>3</sup>Department of Clinical Sciences, College of Veterinary Medicine, and Environmental Medicine Consortium, North Carolina State University, Raleigh, NC 27606, USA. <sup>4</sup>Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27696, USA. <sup>5</sup>Hammer and Hammer Paleotek, 260 Dutchman View Drive, Jacksonville, OR 97530, USA. <sup>6</sup>595 North Main Street, Ashland, OR 97520, USA.

\*To whom correspondence should be addressed. E-mail: Paul\_Fisher@ncsu.edu

## REPORTS

of intermediate or high metabolic rates, as demonstrated by oxygen isotope gradients across individual skeletons, was similar in large theropods (tyrannosaurids) and ornithischians (hadrosaurids and ceratopsids) (5). Here we report the discovery of a four-chambered heart with a single systemic aorta, similar to the arrangement found in birds and mammals, in a specimen of a small herbivorous ornithischian dinosaur.

The specimen, housed in the paleontological collections of the North Carolina State Museum of Natural Sciences (specimen number NCSM 15728), was discovered and prepared by one of us (M. Hammer), who found it in a poorly consolidated channel sandstone exposed in the upper half of the Hell Creek Formation (Maastriichtian) in Harding County, northwestern South Dakota, USA. The extremities and left side of the skeleton were lost to erosion. The specimen is otherwise very well preserved and contains abundant evidence of tissues that usually decay, such as sternal ribs and cartilaginous plates attached to caudal surfaces of thoracic ribs. The skeleton closely resembles that of the hypsilophodontid *Thescelosaurus* (6), and its gracile dentary separates it from fragmentary material of the closely related and sympatric *Bugenasaura* (7). The circumference of the femur (197 mm) suggests a body weight of 300 kg (8), and the length of the femur (468 mm) scales to a total body length of 3.9 m (9). A

large ferruginous concretion is present in the pericardial region of the thoracic cavity.

With one recent exception (10), traces of viscera have not been reported within the thoracic cavity of dinosaurs. To determine whether the concretion contained internal structures, the specimen was imaged in left lateral recumbency with a Picker PQ6000 computerized tomography (CT) scanner at 120 kV potential, 320 mA·s, with a slice thickness of 4 mm and spacing of 2 mm. The images were transferred to a SUN workstation and placed in an ANALYZE-AVW for analysis, thereby clarifying three-dimensional (3D) structures within the concretion. Patterns of shapes and radiodensities were found to resemble a four-chambered heart (Figs. 1 and 2). Two adjacent cavities surrounded by iron-rich walls are readily apparent, connected to a dorsally arched tube in a position that is topologically appropriate for a systemic aorta. The thicknesses of the walls delimiting the cavities are consistent with those of ventricles and an interventricular septum, the relative dimensions of which would vary with the degree of distension of the heart at death. The atria are usually very thin-walled compared to the ventricles and often collapse at death, obliterating their internal cavities. They are not reliably discernable in the specimen, nor are the small vessels that are expected in the region of the putative heart base. A radiolucent area imme-

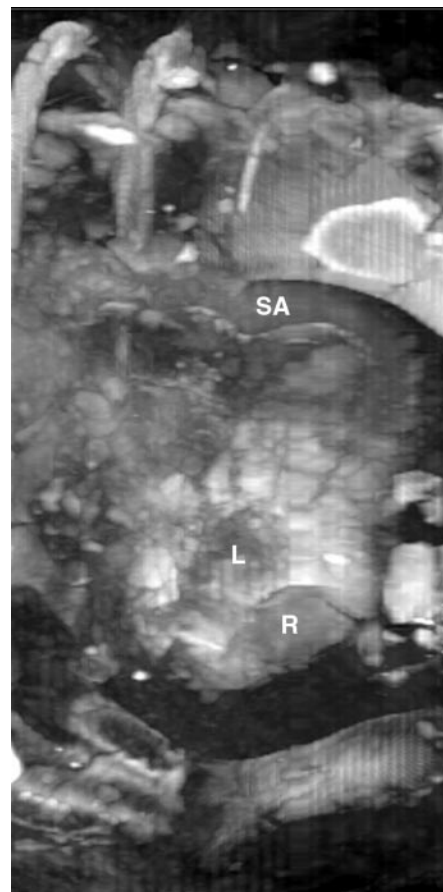
diately adjacent to the systemic aorta, in what would be expected to be lung fields, does not have any surrounding structural detail to suggest that it is associated with the cardiovascular system.

X-ray diffraction (XRD) analyses indicate an abundance of the mineral goethite (alpha FeO-OH) in areas interpreted in the CT scans as ventricle walls, with iron-free quartz silt filling the cavities. Goethite was not found in any of the surrounding sediments or bones. We suggest that iron-bound oxygen in the muscular walls mineralized to goethite while in contact with groundwater during early diagenesis. A separated piece of a wall shows no visible indication of fibrous tissues. Although the geochemical processes involved have not been well studied (11), the structures preserved in the pericardial region may have been preserved through a process (saponification) whereby muscle hydrolyzes under anaerobic conditions (12) and subsequently petrifies.

The presumed systemic aorta arises from the left ventricle and measures approximately 27 mm in diameter near its origin. There are no indications of the presence of a second aortic arch. If similar to conditions in extant crocodiles, the latter arch would be of similar



**Fig. 1.** Right lateral view of a 3D reconstruction of CT images of the *Thescelosaurus* specimen showing the right (R) and left (L) ventricular cavities, preserved sternal ribs (S), and plates resembling uncinata processes (U) attached to thoracic ribs. The apex of the heart has been temporarily removed.



**Fig. 2.** Enlarged right lateral view of a 3D reconstruction of CT images of the same specimen showing the systemic arch (SA) and right (R) and left (L) ventricular cavities.

size and wall thickness and would emerge from the heart in close proximity to the identified arch. It is not possible to deduce the embryologic origin of the single aorta, to verify whether its development paralleled that of birds or mammals (13, 14). The radiographic topology of the aorta is essentially identical in adults of both groups (15). The estimated weight of the heart, based on axial and transverse measurements, a 20% compression effect on a conic volume, and a tissue density of 1 gm/cm<sup>3</sup>, ranges between 1.6 and 1.9 kg, which is quite consistent with predictions (1.5 to 1.8 kg) from regressions based on body weight (16). We do not possess evidence that would allow us to reliably identify other structures within the pericardial region. However, the preservation of heartlike structures within an uncrushed thoracic cavity of one small dinosaur suggests that well-preserved vertebrate skeletons should routinely be examined for traces of non-osseous tissues.

In general terms, dinosaurs appear to have been morphologically intermediate between modern crocodiles and birds. This has led to the inference that the heart of ancestral dinosaurs might have resembled that of crocodiles (1), in which left and right systemic aortas are present and are linked by a foramen of Panizza. This foramen can allow either right-to-left or left-to-right shunting of blood, depending on the phase of the cardiac cycle and a variety of physiological variables, including the activity level of the animal, that affect heart contractility and vascular resistance (17). Reid (1) has suggested that in dinosaurs the foramen of Panizza was closed, and the blood from the left ventricle flowed into a single (right) systemic aorta, as in birds. The basis for his speculation is the need to generate pressure sufficient to circulate blood throughout the body of a large erect animal. We suggest that the primary advantage of this adaptation was to improve systemic oxygenation, thereby supporting higher metabolic rates. It is hypothesized that physiologically controlled right-to-left shunting confers advantages on animals with low metabolic rates by, among other things, reducing cardiac energy requirements (18), although this has recently been questioned (17). In birds and mammals, shunting is clearly detrimental. It diminishes an animal's tolerance for sustained exercise by reducing the efficiency of systemic oxygen delivery to tissues with a generally much higher oxygen demand than those of living ectotherms. A four-chambered cardiovascular system with a single systemic aorta communicating with the left ventricle greatly reduces the risk of shunting and can be considered a means of more efficiently supporting prolonged periods of high activity.

Of the many clades of dinosaurs (4), in at least one (hypsilophodontids) there is now

evidence of an advanced heart with a single systemic aorta. Because of the presence of similar hearts in birds, which are generally considered to be theropod derivatives (3, 4), it might be concluded that ancestral dinosaurs also possessed an advanced heart (thus making the attribute a synapomorphy for dinosaurs). However, in view of the enormous span of time (>150 million years) separating ancestral dinosaurs from the specimen under consideration (4), we are uncertain that the effects of long-term parallel selection and evolution on the cardiovascular system were negligible. Whether high metabolic rates and advanced hearts arose once or more than once among dinosaurs remains an open question.

References and Notes

1. R. E. H. Reid, in *The Complete Dinosaur*, J. O. Farlow and M. K. Brett-Surman, Eds. (Indiana Univ. Press, Bloomington, IN, 1997), pp. 449–473.
2. J. O. Farlow, in *The Dinosauria*, D. B. Weishampel, P. Dodson, H. Osmolska, Eds. (Univ. of California Press, Berkeley, CA, 1990), pp. 43–55.
3. K. Padian, *Nature* **393**, 729 (1998).
4. P. C. Sereno, *Science* **284**, 2137 (1999).
5. R. E. Barrick, M. K. Stoskopf, W. J. Showers, in *The Complete Dinosaur*, J. O. Farlow and M. K. Brett-Surman, Eds. (Indiana Univ. Press, Bloomington, IN, 1997), pp. 474–490.
6. C. W. Gilmore, *Proc. U.S. Natl. Mus.* **49**, 501 (1915).
7. P. M. Galton, *Rev. Paleobiol.* **16**, 231 (1997).
8. J. F. Anderson, A. Hall-Martin, D. A. Russell, *J. Zool. (London)* **207**, 53 (1985).
9. G. S. Paul, in *Dinofest International: A Symposium*

*Sponsored by Arizona State University*, D. L. Wolberg, E. Stump, G. Rosenberg, Eds. (Academy of Natural Sciences, Philadelphia, 1997), pp. 129–154.

10. C. Dal Sasso and M. Signore, *Nature* **392**, 383 (1998); J. A. Ruben et al., *Science* **283**, 514 (1999).
11. M. J. Benton, *Trends Ecol. Evol.* **13**, 303 (1998).
12. J. Weigelt, *Recent Vertebrate Carcasses and Their Paleobiological Implications* (Univ. of Chicago Press, Chicago, 1989).
13. H. Butler and B. H. J. Juurlink, *An Atlas for Staging Mammalian and Chick Embryos* (CRC Press, Boca Raton, FL, 1987).
14. A. Feduccia and E. McCrady, *Torrey's Morphogenesis of the Vertebrates* (Wiley, New York, ed. 5, 1991).
15. D. E. Thrall, *Textbook of Veterinary Diagnostic Radiology* (Saunders, Philadelphia, ed. 3, 1998).
16. F.V. Paladino, J. R. Spotila, P. Dodson, in *The Complete Dinosaur*, J. O. Farlow and M. K. Brett-Surman, Eds. (Indiana Univ. Press, Bloomington, IN, 1977), pp. 491–504.
17. J. W. Hicks, in *Reptiles: Mechanisms, Regulation and Physiological Function*, vol. 19 of *Biology of the Reptilia*, C. Gans and A. S. Gaunt, Eds. (Society for the Study of Amphibians and Reptiles, Ithaca, NY, 1998), pp. 425–483.
18. W. W. Burggren and S. J. Warburton, *Cardioscience* **5**, 183 (1994).
19. The authors are grateful to B. Bennett and V. Schneider of the North Carolina State Museum of Natural Sciences for access to the specimen, to W. H. Straight for XRD analyses, and to R. Lea for his advice and encouragement. A.K. thanks D. Perry for the CT scans; the Ashland Community and Rogue Valley hospitals for access to CT equipment; and cardiologists of Cardiology Consultants PC of Medford, OR, for their comments on the possible fossil cardiac structures. T. Jetton assisted M.H. in the preparation of the dinosaur specimen.

9 March 2000; accepted 27 March 2000

## A Structural Framework for Deciphering the Link Between I-A<sup>G7</sup> and Autoimmune Diabetes

Adam L. Corper,<sup>1\*</sup> Thomas Stratmann,<sup>2\*</sup> Vasso Apostolopoulos,<sup>1</sup> Christopher A. Scott,<sup>1†</sup> K. Christopher Garcia,<sup>1‡</sup> Angray S. Kang,<sup>1§</sup> Ian A. Wilson,<sup>1||</sup> Luc Teyton<sup>2||</sup>

Susceptibility to murine and human insulin-dependent diabetes mellitus correlates strongly with major histocompatibility complex (MHC) class II I-A or HLA-DQ alleles that lack an aspartic acid at position β57. I-A<sup>G7</sup> lacks this aspartate and is the only class II allele expressed by the nonobese diabetic mouse. The crystal structure of I-A<sup>G7</sup> was determined at 2.6 angstrom resolution as a complex with a high-affinity peptide from the autoantigen glutamic acid decarboxylase (GAD) 65. I-A<sup>G7</sup> has a substantially wider peptide-binding groove around β57, which accounts for distinct peptide preferences compared with other MHC class II alleles. Loss of Asp<sup>β57</sup> leads to an oxyanion hole in I-A<sup>G7</sup> that can be filled by peptide carboxyl residues or, perhaps, through interaction with the T cell receptor.

MHC genes have been linked with susceptibility in almost all autoimmune diseases (1). In the case of insulin-dependent diabetes mellitus (IDDM), a role for particular murine I-A alleles and their human homologs, HLA-DQ, has been inferred from numerous studies. Sequence analysis of these alleles has highlighted the importance of a key residue, β57; an Asp at position 57 of the class II β-chain

is correlated with IDDM resistance, while neutral residues Ser, Ala, or Val are linked to disease susceptibility (2, 3).

The nonobese diabetic (NOD) mouse provides a model system for the study of IDDM. I-A<sup>G7</sup> is the only MHC class II molecule expressed in NOD mice and is strongly linked to disease susceptibility. I-A<sup>G7</sup> shares the same α chain as the non-IDDM-linked