

Unidirectional pulmonary airflow patterns in the savannah monitor lizard

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The unidirectional airflow patterns in the lungs of birds have long been considered a unique and specialized trait associated with the oxygen demands of flying, their endothermic metabolism¹ and unusual pulmonary architecture^{2,3}. However, the discovery of similar flow patterns in the lungs of crocodylians indicates that this character is probably ancestral for all archosaurs—the group that includes extant birds and crocodylians as well as their extinct relatives, such as pterosaurs and dinosaurs^{4–6}. Unidirectional flow in birds results from aerodynamic valves, rather than from sphincters or other physical mechanisms^{7,8}, and similar aerodynamic valves seem to be present in crocodylians^{4–6}. The anatomical and developmental similarities in the primary and secondary bronchi of birds and crocodylians suggest that these structures and airflow patterns may be homologous^{4–6,9}. The origin of this pattern is at least as old as the split between crocodylians and birds, which occurred in the Triassic period¹⁰. Alternatively, this pattern of flow may be even older; this hypothesis can be tested by investigating patterns of airflow in members of the outgroup to birds and crocodylians, the Lepidosauromorpha (tuatara, lizards and snakes). Here we demonstrate region-specific unidirectional airflow in the lungs of the savannah monitor lizard (*Varanus exanthematicus*). The presence of unidirectional flow in the lungs of *V. exanthematicus* thus gives rise to two possible evolutionary scenarios: either unidirectional airflow evolved independently in archosaurs and monitor lizards, or these flow patterns are homologous in archosaurs and *V. exanthematicus*, having evolved only once in ancestral diapsids (the clade encompassing snakes, lizards, crocodylians and birds). If unidirectional

airflow is plesiomorphic for Diapsida, this respiratory character can be reconstructed for extinct diapsids, and evolved in a small ectothermic tetrapod during the Palaeozoic era at least a hundred million years before the origin of birds.

The lungs of lepidosaurs have been assumed to be ventilated tidally, an idea based on their bronchial architecture¹¹, but direct measurements of flow are lacking. Furthermore, fluid dynamics are often non-intuitive, and phenomena such as Venturi effects can result in complicated patterns of flow. It is important to characterize patterns of flow in lizards to assess the evolutionary history of the vertebrate lung. Varanids (73 species) are a widely distributed group of anguimorph lizards¹² with the oldest unambiguous fossil appearance of *Varanus* from the Upper Eocene and Lower Oligocene epochs of Egypt¹³. The external morphology of the genus *Varanus* is superficially conservative; however, they vary in mass by almost five orders of magnitude and occupy a range of ecological niches (semi-aquatic to arboreal)^{14,15}. Compared to other lepidosaurs, varanids have high aerobic capacities, with *Varanus caudolineatus* having one of the highest rates of oxygen consumption ever recorded in a non-avian reptile¹⁶. High gas exchange capacities of varanids arise in part from their ability to supplement costal breathing with gular pumping¹⁷. These lizards possess multichambered (that is, multibronchial) lungs (Fig. 1a–e), which have long been used as a phylogenetic character for Varanoidea¹⁸, and thus varanid pulmonary anatomy has received considerable attention^{18–22}.

Varanid lungs are large, structurally asymmetrical and multichambered^{11,20} (Supplementary Video 1 and Fig. 1a–c). The dorsal surface is firmly attached to the ribs along most of their lengths²¹. The primary bronchus runs the length of the lung, ballooning into a large sac-like bronchus just distal to the ostium of the caudal-most lateral bronchus (As in Fig. 1b). The general arrangement of the secondary bronchi arising from the intrapulmonary primary bronchus follows what appears to be a stereotyped branching pattern. Without corroborating developmental data to support this observation, suppositions of bronchial identity remain tentative. Nevertheless, the anatomy of the adult bronchial tree can be visualized from computed tomography (CT) data of individual specimens of *V. exanthematicus*. The first bronchus to arise from the primary bronchus (the cervical bronchus, Cb) has a cartilaginous tube-shaped ostium that

immediately makes a hairpin turn, running cranially and expanding into a large tubular bronchus terminating at the apex of the lung (Cb in Fig. 1c). This bronchus is anatomically reminiscent of the cervical ventral bronchus in crocodylians^{6,9}. Arising sequentially from the lateral surface of the primary bronchus is a series of 9 to 11 variably shaped large sac-like bronchi, termed lateral bronchi (L1–10 in Fig. 1c).

Lateral bronchi communicate with the adjacent bronchi through numerous small intercameral perforations. A similar series of sequentially arranged sac-like bronchi arise off of the medial surface of the primary bronchus from small ostia and run caudomedially, rotating to a ventromedial position. Depending upon the individual, either the first or second medial bronchus on (usually) the right lung extends cranially along the ventral surface of the lung, terminating just distal to the carina. This bronchus is much smaller in the left lung and does not extend cranially. Along the dorsal surface of the primary bronchus in both lungs, small sac-like bronchi emerge in an asymmetrical pattern (Ssb in Fig. 1b). The respiratory parenchyma is largely restricted to the central and craniodorsal regions of the lung, with the saccular regions positioned at the cranial tip and caudoventral areas²¹. Small tertiary bronchi extend towards the pleural surface, forming hexagonal faveolar parenchyma^{11,21}.

The airflow patterns in *V. exanthematicus* are heterogeneous, with tidal and unidirectional flow observed in different regions of the lungs. Unidirectional airflow was measured using heated thermistor flow meters *in vivo* ($n = 5$) and in excised lungs ($n = 9$) in the caudal-most, large lateral bronchus (generally L10, depending upon the individual) (Fig. 1c, d and Fig. 2a–c). Flow was also observed by visualizing the movements of microspheres and pollen suspended in water in excised lungs ($n = 5$; Supplementary Video 2). Tidal flow was recorded in a cranial lateral bronchus (excised, $n = 2$), whereas unidirectional flow was observed visually in the rest of the lateral bronchi (L2–L10; $n = 4$) and the cervical bronchus ($n = 4$). Biased flow (that is, a significantly stronger magnitude of flow present during only one phase of the respiratory cycle) was measured in the abdominal sac-like bronchus (with thermistors ($n = 4$) and microspheres ($n = 4$) in excised lungs), with air arriving dorsally via the primary bronchus during inspiration, travelling caudoventrally to the caudal surfaces of the last lateral bronchus and through the intercameral perforations along the shared bronchial walls during expiration (Fig. 1e).

Flow between the lateral bronchi is interbronchial unidirectional flow, meaning that the flow travels in the same direction from one bronchus to another during both phases of the respiratory cycle.

These observations thus constitute evidence supporting the conclusion that the global pattern of flow in the bronchial tree of *V. exanthematicus* is predominantly unidirectional, composed of cranial and caudal regions of unidirectional airflow (Fig. 1e). Flow in the cervical bronchus appears to maintain its one-way direction by jetting in association with the anatomy of the ostium and proximally constricted bronchus, coupled with connections to small tertiary bronchi (Tb in Fig. 1b). Flow between the lateral bronchi is probably also maintained via jetting, in conjunction with the branching angle of each individual bronchus relative to the primary bronchus and the proximal constriction of each bronchus, thus constituting aerodynamic valving. The flow between bronchi is possible because of intercameral perforations, much like those found in archosaur lungs, despite the differences in their respective bronchial architecture. Aerodynamic valves arise from the geometry and branching angles of the primary and secondary bronchi, with valving mediated by the convective momentum of gas flow in this particular geometry. We suggest that this is the mechanism biasing flow in one direction in the lung of *V. exanthematicus*, owing to the absence of any physical flaps or muscular sphincters within their bronchial tree, and because flow patterns were unchanged in excised lungs. Thus it appears that the flow arises from the same aerodynamic phenomena seen in the archosaurian lung⁷.

Unidirectional flow patterns have been measured in both avian and crocodylian lungs, indicating that this trait is probably plesiomorphic for Archosauria. The presence of unidirectional flow in regions of the lung of *V. exanthematicus* thus raises two hypotheses reflecting different evolutionary scenarios (Fig. 3). The first hypothesis is that unidirectional flow patterns evolved independently in both Archosauria and Lepidosauria, and are a convergent apomorphy of both groups. The alternative hypothesis is that this pulmonary character is homologous in archosaurs and *V. exanthematicus*, having evolved only once, and is thus the ancestral state for diapsids (Lepidosauria + Archosauria). Relative to other lepidosaurs, varanids are particularly derived with a substantially more complex bronchial arrangement than their more basal relatives (see Fig. 3)^{11,23}. The

structure of varanid airways is different from that of archosaurs, both in terms of bronchial geometry as well as its branching sequence along the primary bronchus, making it difficult to favour one evolutionary scenario over the other. The presence of archosaur-like aerodynamic valves and unidirectional flow in the varanid lung suggests that this trait evolved in ancestral diapsids. However, differences in the patterns of flow between varanids (caudal to cranial in the ventrolateral sac-like bronchi) and archosaurs (caudal to cranial in the dorsal tube-shaped secondary bronchi) coupled with notable differences in the arrangement of the secondary bronchi, can only be interpreted as convergent until the airflow patterns in more basal lepidosaurs are measured (Fig. 3). Owing to the considerable amount of variability in the lepidosaurian respiratory system, both across the entire clade as well as within individual groups, it will be essential to investigate flow patterns in multiple representative species from each major group (for example, *Sphenodon*, Iguania, Gekkota, Scincomorpha and other non-varanid anguimorphs) to shed light on this question (Fig. 3).

Determining when unidirectional airflow patterns first evolved has implications for understanding both the origin and function of respiratory patterns in non-avian reptiles, as well as reconstructing lung physiology and morphology in extinct taxa. If demonstrated to be ancestral for Diapsida, unidirectional airflow patterns can be parsimoniously reconstructed in all extinct diapsids. If these flow patterns evolved convergently between varanids and archosaurs, then this would suggest that the ability to ventilate unidirectionally holds an adaptive significance to these taxa.

METHODS SUMMARY

In vivo data were collected from five live specimens of *Varanus exanthematicus* (mass 350 g–930 g), and *ex vivo* data from ten specimens. Animals were acquired from the California Zoological Supply (live) and donated by J. Dix, Utah's Reptile Rescue Service (deceased). All experiments were performed in accordance with and approved by the University of Utah Institutional Animal Care and Use Committee. Three individuals were CT-scanned at 100 peak kilovolts (kVp) and 400 milliamp tube current. A series of images were made along the long axis of the lungs. The thickness of each image (slice) was 0.6 mm and the slices were made at intervals of 0.4 mm along the long axis such that

0.2 mm of each slice overlapped with the previous slice. Digital models of the bronchial tree were segmented using Avizo version 7.1 (<http://www.vsg3d.com/avizo/standard>). Measurements of airflow were made with dual heated thermistor airflow probes surgically implanted into individual bronchi. The probes were connected to an HEC 132C Thermistor Flowmeter (Hector Engineering). The analogue output was converted to a digital signal (Biopac Systems) and recorded on a computer using AcqKnowledge software (Biopac Systems). Airflow at the nares was measured with a pneumotach (Hans Rudolph Inc.). Flow traces in live animals were recorded during hypercapnic breathing; traces measured in excised lungs were acquired from artificial ventilation (60 cm³ syringe). Videos of the movement of saline containing microspheres (222 μm in diameter, Thermo Scientific) and pollen through excised lungs were taken with a Canon EOS T2i (resolution of 1080 pixels) digital camera. The raw CT data are available from the Dryad Digital Repository at <http://doi.org/10.5061/dryad.v1d30>.

Received 9 August; accepted 6 November 2013; doi:10.1038/nature12871.

Published online December 11th, 2013.

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Supplementary Information is available in the online version of the paper.

Acknowledgements We thank J. Dix (Reptile Rescue Service) for the donation of deceased varanid specimens, J. Bourke for assistance with Avizo, and D. Shafer for German translations. This work was supported by an American Association of Anatomists Postdoctoral Fellowship and an American Philosophical Society Franklin Research Grant to E.R.S., National Science Foundation grants to C.G.F. (IOS-1055080 and IOS-0818973) and a generous donation to the Farmer laboratory by S. Meyer.

Author Contributions E.R.S. and R.L.C. conducted the *in vivo* surgeries. All authors collected data on excised lungs. E.R.S. acquired the CT scans and generated the three-dimensional digital models. C.G.F. and J.P.B. supervised and contributed ideas throughout the project. All authors contributed to the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to E.R.S. (eschachner@gmail.com) or C.G.F. (cg.fmr@gmail.com).

Figure 1 Pulmonary anatomy and airflow patterns of *Varanus exanthematicus*. **a**, Volume rendered skeleton and segmented lungs. **b**, Solid representation of the bronchial tree. Tb, tertiary bronchi; Ssb, secondary sac-like bronchi; As, abdominal sac-like bronchus. **c**, Same as **b** with tertiary and medial bronchi removed. Cb, cervical bronchus; L1–L10, lateral bronchi 1–10. **d**, Bronchi in which flow was measured in excised lungs (orange/grey), and *in vivo* in this animal (pink). **e**, A diagram of the lung with arrows showing the direction of measured airflow (L5, L7, L9, L10 and abdominal sac). Paired large and small arrows indicate biased flow, blue arrows indicate interbronchial flow.

Figure 2 Airflow recorded *in vivo*. **a**, Left lateral view of the left excised and inflated lung of *Varanus exanthematicus*. The arrow indicates where the airflow probe was surgically implanted for all *in vivo* measurements. Numbers represent regions where flow was recorded in excised lungs: 1, cervical bronchus (excised: $n = 2$; saline: $n = 4$); 2, last lateral bronchus (*in vivo*: $n = 5$; excised: $n = 9$; saline: $n = 4$); 3, abdominal sac (excised: $n = 4$, saline: $n = 4$). Scale bar = 1 cm. **b**, Tidal airflow measured at the nares. Shaded

regions show inhalation, unshaded regions show exhalation. **c**, Largely unidirectional flow in L10; flows indicate directionality, not actual magnitudes.

Figure 3 Phylogeny for Diapsida showing lungs of representative taxa. Greyscale images are modified from Milani^{24,25} and transected. The coloured three-dimensional images are the bronchial tree (right lateral view). Images are not to scale. **a**, Diapsida. **b**, *Sphenodon punctatus*. **c**, Crocodile sp. (left) and *Alligator mississippiensis* (right). **d**, Squamata. **e**, *Iguana iguana* (left) and *Polychrus marmoratus* (right). **f**, *Gekko gecko*²⁶. **g**, *Lacerta viridis*. **h**, *Python sp.* in dorsal view²³. **i**, *Varanus bengalensis* (left) and *V. exanthematicus* (right). The blue regions of the phylogeny reflect the hypothesis that unidirectional airflow evolved convergently; the green arrow shows the alternative hypothesis of an ancestral origin.

METHODS

Twelve animals were used in this study, and were acquired from the California Zoological Supply (live) and J. Dix, Utah's Reptile Rescue Service (deceased). No animals were excluded from the analysis. No randomization or blinding was done, and no statistical tests were used in this study. The animals were all *Varanus exanthematicus*, of largely unknown gender and age (mass 350 g–930 g). *In vivo* data were collected from five live specimens of *V. exanthematicus*. Data were collected from the excised lungs of ten specimens of mixed sex and unknown age. All experiments were performed in accordance with and approved by the University of Utah Institutional Animal Care and Use Committee. Three individuals were CT-scanned at 100 peak kilovoltage (kVp) and 400 tube current. A series of images were made along the long axis of the lungs. The thickness of each image (slice) was 0.6 mm and the slices were made at intervals of 0.4 mm along the long axis such that 0.2 mm of each slice overlapped with the previous slice. Digital models of the bronchial tree, lung surface and skeleton were segmented by hand in Avizo version 7.1 (<http://www.vsg3d.com/avizo/standard>) using a Wacom Intuos4 pen tablet. The images were edited into figures in Adobe Photoshop CS6, and the three-dimensional files exported from Avizo were edited into a video file in Adobe Premiere CS6. Measurements of airflow were made with dual heated thermistor airflow probes

surgically implanted into individual bronchi of the lungs. The probes were connected to an HEC 132C Thermistor Flowmeter (Hector Engineering). The analogue output was converted to a digital signal (Biopac Systems) and recorded on a laptop using AcqKnowledge software (Biopac Systems). Airflow at the nares was measured with a pneumotach (Hans Rudolph Inc.). Flow traces in live animals were recorded as they breathed hypercapnic gas; traces measured in excised lungs were acquired from artificial ventilation (60 cm³ syringe). Five of the smaller lungs were excised and filled with microspheres (222 μm in diameter, Thermo Scientific) infused saline and pollen grains. Video of movement of the microspheres was recorded with a Canon EOS T2i (resolution of 1080 pixels) digital camera. The raw CT data are available from the Dryad Digital Repository at <http://doi.org/10.5061/dryad.v1d30>.

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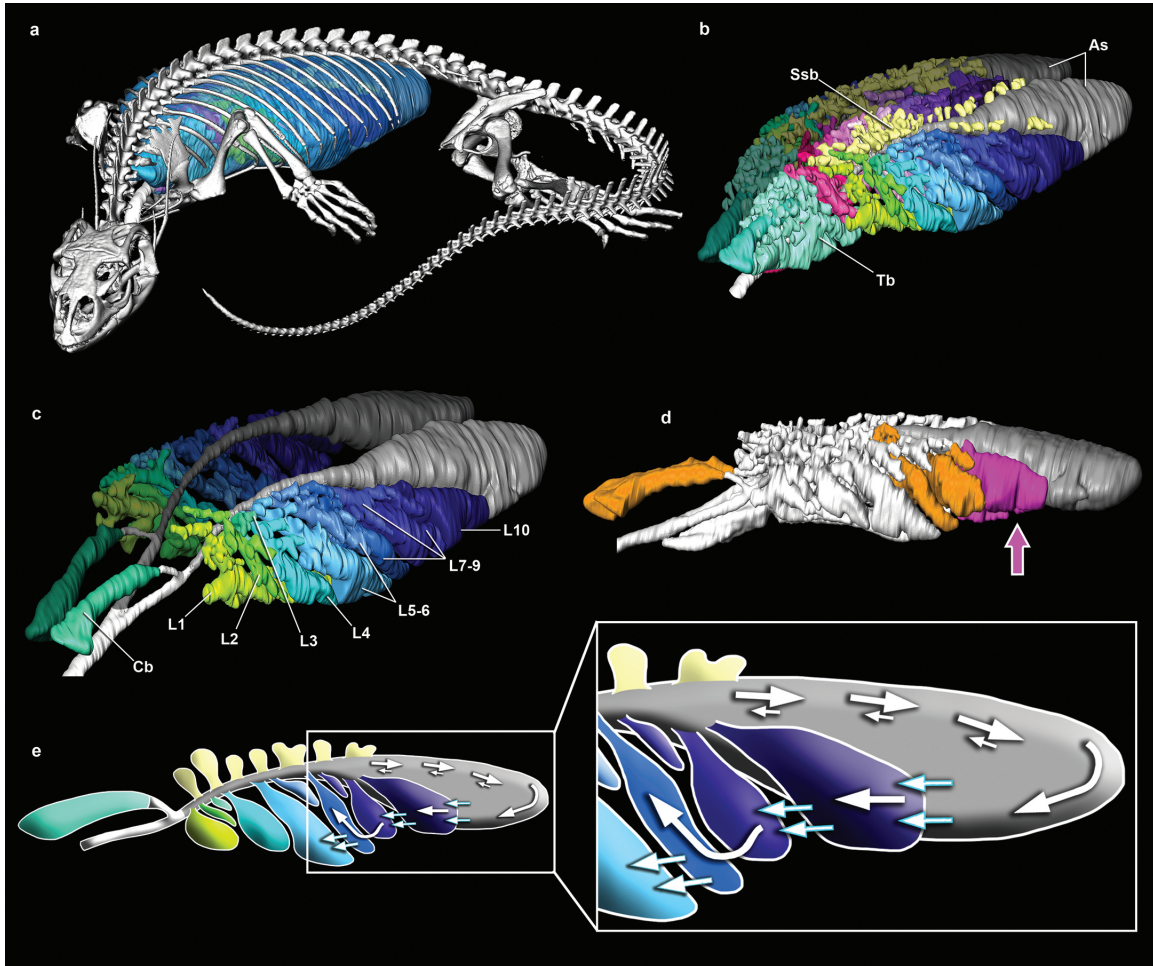


Figure 2 Airflow recorded *in vivo*.

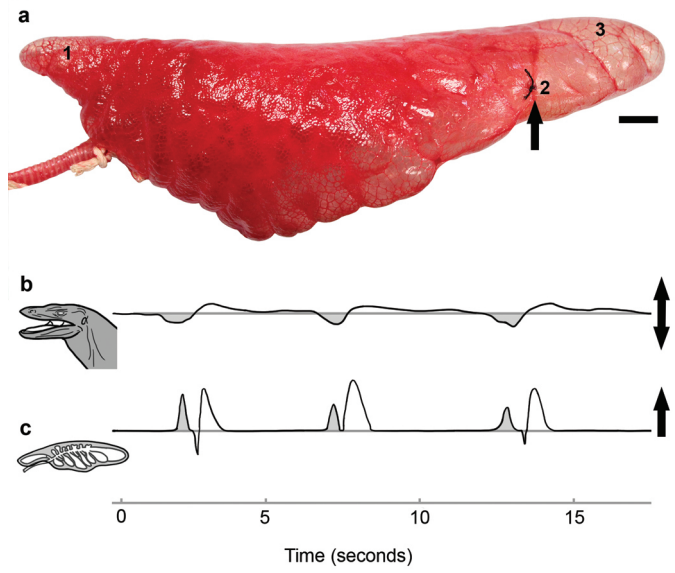


Figure 3 Phylogeny for Diapsida showing lungs of representative taxa.

