COMPUTATIONAL FLUID DYNAMICS INVESTIGATION INTO PULMONARY AIRFLOW PATTERNS IN MONITOR LIZARDS *(VARANIDAE)*

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EXECUTIVE SUMMARY

This research used computational fluid dynamics modeling to simulate how air flows through the lungs of monitor lizards in order to investigate why there are different types of lung airflow patterns among various types of animals (*e.g.*, birds, mammals, reptiles). The PI found that monitor lizard lungs have a unique net-unidirectional airflow pattern where, although air moves in multiple directions through each part of the lung during breathing, each part transports more air in a certain direction over the whole breath cycle. This fascinating airflow pattern has features in common with both bird lungs (fully unidirectional) and mammal lungs (fully tidal).

RESEARCH CHALLENGE

An important open question in comparative physiology concerns a functional explanation for the variety of lung designs in vertebrates: Why are lungs so diverse? Unidirectionally pulmonary airflow, a condition where certain lung gases travel in a consistent direction during both inspiration and expiration, was long thought to be found only in birds and to have been a requirement for the high metabolic demands of powered flight [3]. Recent work, however, discovered unidirectional flow patterns in alligators, monitor lizards, and iguanas, which are animals that do not fly and have relatively low metabolic rates [4–6]. We thus need research to explain why pulmonary airflow patterns and lung designs vary in vertebrates [7]. Unfortunately, lungs are very small, delicate, and complex, so determining how air flows through them directly is difficult. Computational fluid dynamics (CFD) modeling offers a new approach: Anatomically accurate computational domains can be constructed from computed tomography scans, and simulations of how air flows through the lungs can be point-validated to reconstruct the diversity of pulmonary flow patterns in vertebrates. This project sought to investigate these patterns in monitor lizards, an extremely diverse group of lizards [8] that nonetheless have a conserved body plan and unidirectional pulmonary airflow [6].

METHODS & CODES

CFD simulations were run in OpenFOAM, an open source continuum mechanics library using a custom moving-boundary code based on the SIMPLE algorithm (transientSimpleDyMFoam). Model geometry was segmented from computed tomography scans of a live, anesthetized lizard. Simulation data were visualized in ParaView. Simulations were validated by means of visualization of aerosolized lipids through a microendoscope placed at various points in the lung while the lung was ventilated with a 25 mL syringe. In almost all cases, there was good correspondence between the smoke measurements and the CFD model.

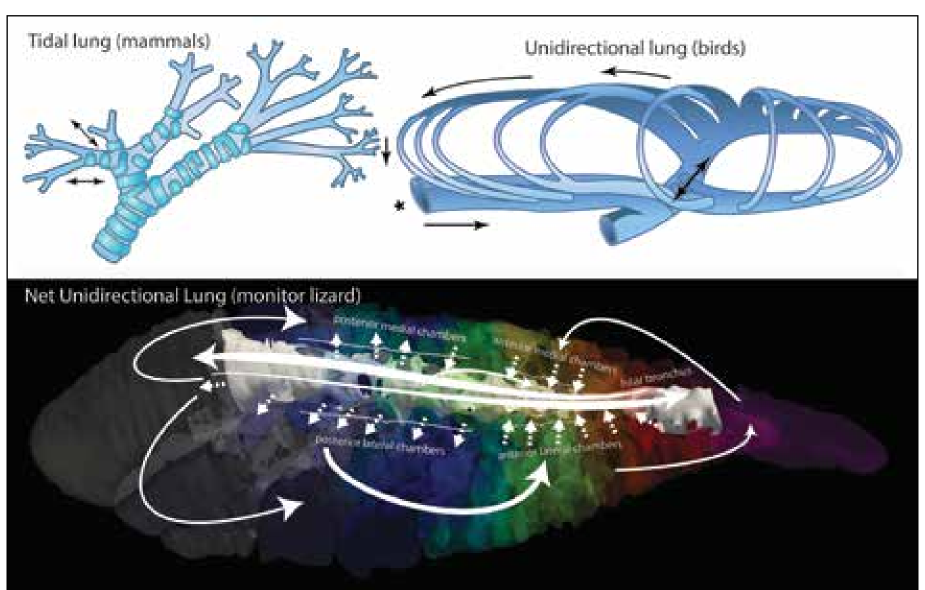

Figure 1: Different types of airflow patterns in animal lungs. Mammals (top left) have a tidal airflow pattern where air moves to and fro through a ramifying network of bronchi. Birds (top right) have looping bronchi and air moves in the same direction during both inspiration and expiration through many of their bronchi. Monitor lizards (below) have a net-unidirectional airflow pattern where air moves to and fro but more air moves forward or backward over the whole ventilatory cycle in each part of the lung. (Top images from [1]; bottom image from [2].)

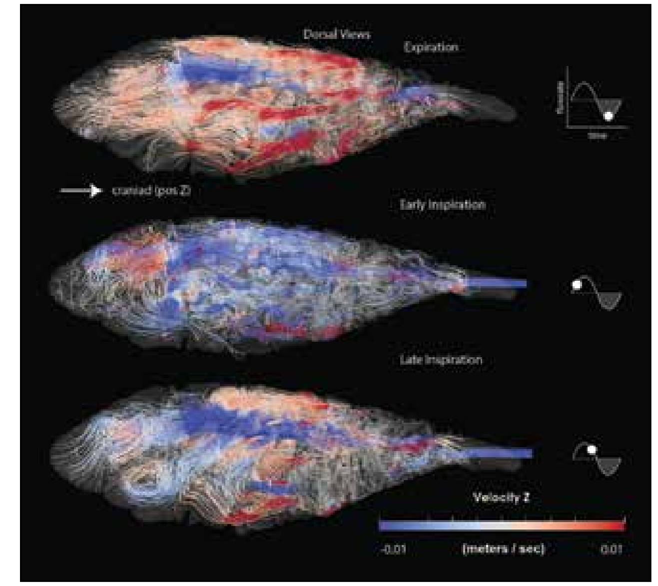

Figure 2: Dorsal views of streamlines from the CFD simulation of pulmonary airflow in monitor lizards run on the Blue Waters machine. Red streamlines indicate flow toward the front of the lung and blue streamlines indicate flow toward the back of the lung. Expiration and late inspiration contain overall similar flow patterns, but early inspiration is largely reversed. (Image from [2].)

RESULTS & IMPACT

The lung of the savannah monitor lizard (*Varanus exanthematicus*) consists of a central intrapulmonary bronchus (IPB) and multiple ostia (openings) into lateral, medial, and dorsal secondary bronchi. The main finding of this investigation is that the pattern of flow in the lung of monitor lizards is uniquely net-unidirectional (Fig. 2). Air flows primarily toward the back of the lung through the distal portion of the IPB and toward the front of the lung through intercameral perforations in the walls of the lateral, medial, and dorsal bronchi. The filigree that separates the bronchi allows the passage of air through a route other than the main IPB and thus has a function for airflow that is similar to the parabronchi of birds. The net-unidirectional flow throughout the lung arises from the collective action of multiple unidirectional bronchi, where the direction of flow often reverses during the ventilatory cycle, such that early inspiratory flow is in a different direction from late inspiratory flow and expiratory flow.

The researcher is not suggesting that the lung of *V. exanthematicus* represents a transitional state; it has a unique airflow pattern that is an interesting blend of features similar to the bird and the iguana lung. Similar to the bird lung, inspired air travels net-caudad (toward the tail as opposed toward the head) through the center of the lung and net-craniad (toward the head) through the walls connecting bronchi within the lungs. Also like the bird lung, the cranial bronchi ostia are net-incurrent and the caudal ostia off the IPB are net-excurrent openings with respect to the IPB. The intercameral perforations in the varanid lung are similar to the parabronchi of birds and even more like the intercameral (within a chamber) perforations of crocodilians [9], in that they move air net-cranially, but in monitors they are simple holes and not elaborate gas-exchange channels. The dorsal bronchi and proximal aspects of the secondary bronchi, on the other hand, are similar to the avian parabronchi in that they are the sites of gas exchange. On the other hand, both the varanid and the iguana lung feature a strong jet of air that bends flow cranially at the caudal aspect of the lung.

WHY BLUE WATERS

With Blue Waters, it was possible to run many models at once to test hypotheses about the importance of different anatomical lung traits on the resulting pulmonary airflow pattern. For example, several models were run where the frequency and size of the intercameral perforations between the lung bronchi were either increased or decreased, the first secondary bronchus was removed, and the type of lung motion was changed. Blue Waters also made possible the timely simulation of multiple breaths, as many simulations calling for hundreds of computational nodes could be computed simultaneously. Finally, a current investigation into how airflow patterns vary between different species of monitors is only possible through Blue Waters because of the sheer number of node hours necessary!

PUBLICATIONS & DATA SETS

R. L. Cieri and C. G. Farmer, "Computational fluid dynamics reveals a unique net-unidirectional pulmonary airflow pattern in the savannah monitor (*Varanus examthematicus*), in review, 2019.

In August 2019, Robert Cieri received a Ph.D. in biology from The University of Utah, where he worked under the direction of C. G. Farmer.