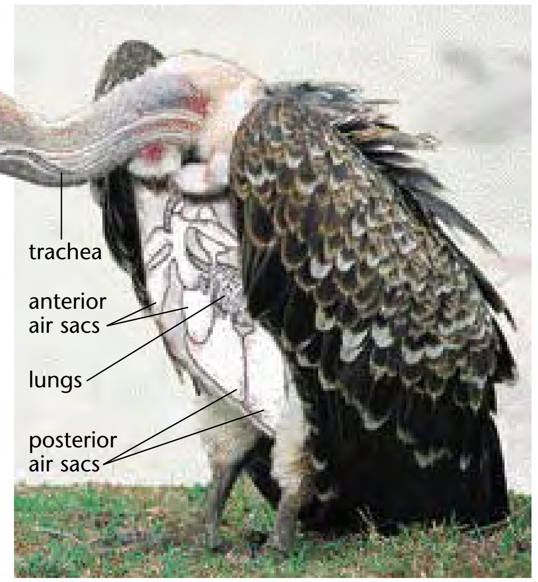
LIFE IN THIN AIR

Birds can survive and function at higher altitudes than any other vertebrates.
They are able to do this because of a unique and highly efficient respiratory system.
In this article, ***Phil Hockey*** *explains the workings of their breathing apparatus.*

Anyone who has searched for endemics on the high mountain plateaux of Ethiopia will certainly have been breathless, and possibly even nauseous, in the thin, low-oxygen highland air at 4 000 metres and higher. Yet the birds around you seem unaffected by the altitude. Even at 8 000 metres in the Himalayas, Alpine Choughs *Pyrrhocorax graculus* are active. A Rüppell's Vulture *Gyps rueppellii* once collided with an aeroplane 11 300 metres above the city of Abidjan – the upper limit for moderate human activity is barely half of this altitude.

Flight is energetically costly, hence uses up large amounts of oxygen. A flying bird consumes more oxygen than a running mammal of the same size. Yet birds can function normally at altitudes where mammals would be comatose. On this evidence alone there must be differences in the respiratory systems of birds and mammals that make birds so much more efficient at extracting oxygen from thin air.

The respiratory system of mammals is fairly simple: two balloon-like lungs are connected to the outside via two bronchi and the trachea. Oxygen enters the bloodstream through capillaries in the lung walls and is replaced by carbon dioxide, which is lost as the mammal exhales. Birds also have two lungs connected to the outside via the trachea, but the lungs themselves are very different in appearance to those of mammals – more resembling a sponge than a balloon. Furthermore, the bird's respiratory system comprises not only two lungs, but also a series of air sacs. These are connected both to the bronchi that pass through the lungs and to the hollow cores of the major bones of the body. The air sacs act as bellows, but oxygen does not pass across the air sac walls and into the bloodstream. As in mammals, oxygen exchange occurs only in the lungs. Although birds' lungs are smaller than mammalian lungs, the total volume of their respiratory system is about three times as large.



Diagrammatic representation of the respiratory system of a Rüppell's Vulture.

To understand how this rather complex system works, it is best to visualise it in three parts – the anterior air sacs (positioned near the front of the bird), the lungs and the posterior air sacs. It is also important to know that the diaphragm of birds works in the opposite way to that of a mammal. As a result, when a bird inhales, the volume of the air sacs increases and that of the lungs decreases! When the bird exhales, the opposite occurs and the lungs increase in volume.

When a bird breathes in, the slug of fresh air passes directly along the bronchi to the posterior air sacs (which increase in size). At the same time, the lungs are compressed by the diaphragm and the stale air that was in them is now forced into the anterior air sacs. When the bird breathes out, the air sacs contract and the lungs expand. The fresh air in the posterior air sacs is forced forwards into the lungs and the stale air in the anterior air sacs is exhaled. An important and unique feature of bird respiration now is apparent: unlike mammals, when a bird breathes out it is not exhaling the air that it took in on the previous breath – that air has only now reached the lungs.

On the next inhalation, the now stale air in the lungs passes to the anterior air sacs and a new slug of fresh air enters the posterior sacs. On exhalation, the original slug of air is now breathed out. Thus, it takes two breaths for one slug of air to pass completely through the system, not one breath as in mammals.

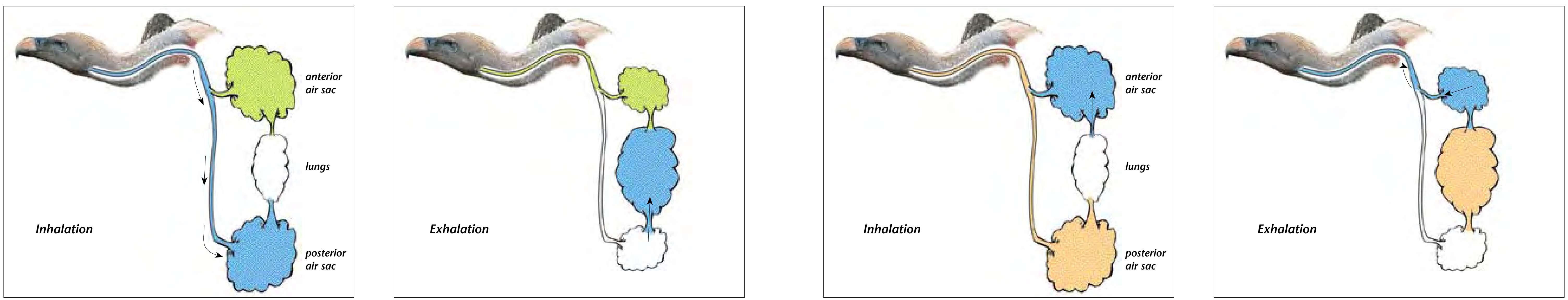
The other key design feature of this system is that air is always passing through the lungs in the same direction, from the back to the front. This is similar to the way in which water passes over the gills of a fish and allows for a specialised and highly efficient alignment of the blood vessels that absorb oxygen. The ability of blood to absorb this gas is determined by the amount of oxygen already in the blood – the more oxygen-rich the blood, the more difficult it is to absorb additional oxygen. Low-oxygen blood can absorb oxygen even if the gas is at low concentration. Oxygen-rich blood needs a very rich oxygen source to be able to absorb more.

Blood arriving at the lungs is oxygen hungry, having passed around the body. Within the lungs, however, oxygen is not evenly distributed. The freshest air is at the back of the lungs. Air at the front of the lungs has been there for longer and is lower in oxygen. The unidirectional flow of air allows for a unidirectional flow of blood – in the opposite direction. This is called a counter-current system and is highly efficient. Oxygen-hungry blood first encounters the lowest oxygen air in the lungs, but nonetheless can extract it efficiently. As the blood passes towards the rear of the lungs, it becomes increasingly saturated with oxygen but it is also constantly moving along a gradient of increasing oxygen concentration. This arrangement allows birds to extract about 25 per cent more oxygen from the air than can mammals, giving them a great advantage over mammals in low-oxygen environments. However, birds have one more arrow in their quiver.

When oxygen is absorbed by the blood, it is attached to a protein called haemaglobin which is found on the surface of red blood cells. Mammals have only one type of haemaglobin, but many migratory birds have two: a low-altitude and a high-altitude form. The latter has an even higher oxygen affinity than normal haemaglobin and birds switch between the two forms depending on the altitude at which they are flying. Interestingly, the world altitude record-holder – Rüppell's Vulture – has no fewer than four types of haemaglobin, but how it uses these is still a mystery.

Their ability to function at high altitude has allowed birds to diversify into some of the highest landscapes on the planet, but the unique respiratory system is not a prerequisite for vertebrate flight. Bats can fly, but have the same breathing apparatus as other mammals. What bats cannot do is live at very high altitudes. They do, however, illustrate very neatly the advantages of flight: they are the only Order of mammals to have evolved true powered flight and, collectively, they account for about one quarter of the living mammal species. □

Photograph adapted from the original by Ariadne Van Zandbergen.



Diagrams showing how it takes two full breaths for one slug of air, shown in blue, to pass through a bird's respiratory system.