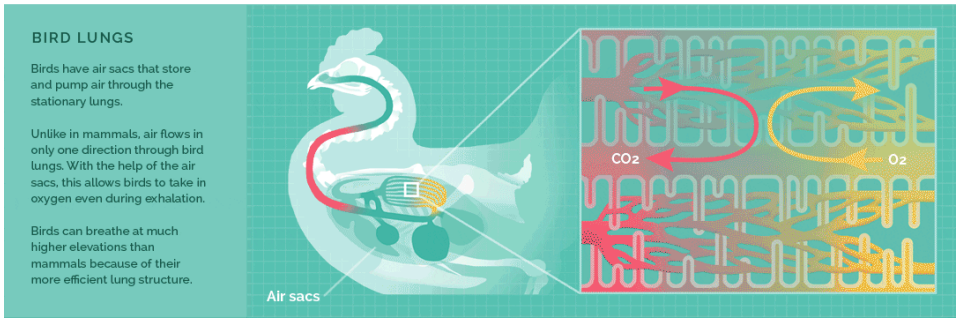
生物策略表

類別	生物策略 (Strategy)
生物策略 STRATEGY	氣囊是如何強化鳥類呼吸系統的肺部 How Air Sacs Power Lungs in Birds' Respiratory System
生物系統 LIVING SYSTEM	鳥類 Birds
功能類別 FUNCTIONS	#儲存空氣 #分配空氣 #排出空氣 #高性能形狀/材質 #Store Gases #Distribute Gases #Expel Gases #Optimize Shape/Materials
作用機制標題	鳥類的呼吸系統透過氣囊維持持續性單向通過肺部的氣流以助於高效率的氧氣與二氧化碳交換 The respiratory system of birds facilitates efficient exchange of carbon dioxide and oxygen by using air sacs to maintain a continuous unidirectional airflow through the lungs.
生物系統/作用機制示意圖 (確認版權、註明出處；畫質)	 https://asknature.org/wp-content/uploads/2016/06/benoit-gauzere-6CcoF7h9h-k-unsplash-scaled-1440x960.jpg  Image by Eleanor Lutz / tabletopwhale.com
作用機制摘要說明 (SUMMARY OF FUNCTIONING MECHANISMS)	

鳥類的呼吸系統與哺乳類的呼吸系統有著物理性質上的不同，不論是結構還是氣體交換能力都更加有效率。

鳥類的呼吸系統由成對的肺組成，肺有著用於氣體交換的靜態結構、連接著的氣囊，氣囊擴張並造成空氣流經靜態的肺部。一個被吸入且含豐富氧氣的空氣將在氧氣被消耗殆盡前經歷兩輪的吸、吐，並被排出體外。

當新鮮空氣首先被吸入一隻鳥的鼻孔 (nares (nostrils))，它將行經氣管 (trachea) (一個巨大的管子延伸自喉嚨)，其被分開成左及右的主要支氣管 (bronchi) (又名中支氣管，有兩個管子至肺部)。吸入的空氣沿著所有主支氣管並分開：有些進入用於氣體交換的肺部，而其餘的空氣則將後氣囊 (posterior (rear) air sac) 填滿。接著在首次吐氣 (exhalation) 時，在後氣囊內的新鮮空氣進入肺部並進行氣體交換。消耗過後的空氣 (the spent air) 將被新進的空氣擠開並通過氣管排出。在第二次吸氣時，新鮮的空氣再次進入深處氣囊及肺部。肺部交換後的空氣又一次被進來的空氣推離，但這次不能從氣管離開，因為新鮮空氣正在流入。取而代之的，被使用的空氣自肺部進入前氣囊。接著，當第二次吐氣時，在前氣囊及肺部的空氣將從鼻孔排出，並且後氣囊的新鮮空氣進入肺部進行氣體交換。

通過這種模式的呼吸系統，使之在肺的氣體交換介面上形成單方向的新鮮氣流。並且，不論吸氣或吐氣時，新鮮空氣都會流經氣體交換的介面，這可導致新鮮空氣的持續供應，使鳥類能夠經歷肺部氣體交換近乎連續的狀態。這與空氣能雙向流動的哺乳類肺部形成對比。

鳥類呼吸系統的高效部分多虧了單向性及近支氣管 (肺內一個小區塊) 結構。近支氣管系統壁呼吸毛細管的表面積比哺乳類呼吸系統的表面積大。表面積越大，氣體交換效率越高。
此篇整理自 Alex Uhrich 的文章

The avian respiratory system is physically distinct from the mammalian respiratory system, both in structure and in its ability to exchange gas as efficiently as possible.

The bird’s respiratory system consists of paired lungs, which contain static structures with surfaces for gas exchange, and connected air sacs, which expand and contract causing air to move through the static lungs. A breath of oxygen-rich inhaled air remains in the respiratory system for two complete inhalation and exhalation cycles before it is fully spent (used) and exhaled out the body.

When fresh air is first inhaled through a bird’s nares (nostrils), it travels through the trachea (a large tube extending from the throat), which splits into left and right primary bronchi (a.k.a. mesobronchi, with each bronchus leading to a lung). The inhaled air travels down each primary bronchus and then divides: some air enters the lungs where gas exchange occurs, while the remaining air fills the posterior (rear) air sacs. Then, during the first exhalation, the fresh air in the posterior sacs enters the lungs and undergoes gas exchange. The spent air in the lungs is displaced by this incoming air and flows out the body through the trachea. During the second inhalation, fresh air again enters both the posterior sacs and the lungs. Spent air in the lungs is

again displaced by incoming air, but it cannot exit through the trachea because fresh air is flowing inward. Instead, the spent air from the lungs enters anterior (forward) air sacs. Then, during the second exhalation, the spent air in the anterior sacs and in the lungs flows out through the trachea, and fresh air in the posterior sacs enters the lungs for gas exchange.

This pattern of airflow through the respiratory system creates unidirectional (one-way) flow of fresh air over the gas exchange surfaces in the lungs. Furthermore, fresh air passes over the gas exchange surfaces during both inhalation and exhalation, resulting in a constant supply of fresh air enabling the bird to experience a near-continuous state of gas exchange within the lungs. This contrasts with mammalian lungs, which experience bidirectional airflow over the gas exchange surfaces.

The efficiency of the avian respiratory system is owed in part to its unidirectional nature and the structure of its parabronchial system (the smaller passages within the lungs). The air capillaries in the walls of the parabronchial system have a much larger overall surface area than that found in the mammalian respiratory system. The greater the surface area, the more oxygen and carbon dioxide can be passed between blood and tissues, which makes for more efficient breathing.

This summary features contributions from Alex Uhrich.

文獻引用 (REFERENCES)

鳥類獨特的肺部讓它們的氣流行徑為單方向，而不是與其他脊椎動物一樣有進有出。當一個鼻孔只能進行吸氣或吐氣時，鳥類是如何控制氣流呢？令人驚奇的解法是由獨特的生理特色及對空氣的操縱。補充肺部的是一套氣囊交互連接的精緻系統，不存在哺乳類…大多的鳥由在喙上的鼻孔呼吸…吸入的空氣沿著氣管向下到支氣管，在支氣管分開並變成更多的細小氣管分支到肺內…大多數肺部組織由大約 1800 個更小、相互連結的第三支氣管組成。這些支氣管導致呼吸毛細管與微血管交織在一起，用以氣體交換。
通過兩個呼吸循環，使吸入的空氣經過四個步驟。大多空氣在第一步被吸入自主要支氣管到後氣囊…第二步，在第一次呼吸的吐氣階段，第一步吸入的空氣會自後氣囊到肺部。在那裡，氧氣及二氧化碳在第一步吸入的空氣流過呼吸毛細系統時進行交換。第三步，少氧的空氣自肺前往前氣囊。第二次，即最後一次吐氣，第四步，自前氣囊、支氣管、氣管到大氣釋放含較高濃度二氧化碳的空氣。
這四步最大化新鮮空氣與肺的呼吸系統表面。最重要的是鳥類在每次呼吸近乎更換了所有的空氣。相對於哺乳類，鳥類的呼吸循環在呼吸時幾乎沒有剩餘的空氣。透過每次呼吸更高的含氧量，鳥類的氣體交換率比哺乳類更多…氣囊系統是個不顯眼，但也是不可或缺、鳥類的一部分…氣囊是薄膜 (只有一到二層膜厚) 結構延伸至翅膀骨及腿骨的空腔…氣囊使持續性、單向及高效的氣流通過肺部成為可能。

“Avian lungs are unique in that the air flows in only one direction, rather than in and out as in other vertebrates. How do birds control the air so that it flows through their lungs when they can only inhale and exhale through one trachea? The solution is a surprising combination of unique anatomical features and the manipulation of airflow. Supplementing the lungs is an elaborate system of interconnected air sacs, not present in mammals…Most birds inhale air through nostrils, or nares, at the base of the bill…Inhaled air moves next down the trachea, or windpipe, which divides into two bronchi and in turn into many subdividing stems and branches in each lung…Most of the lung tissue comprises roughly 1800 smaller interconnecting tertiary bronchi.

These bronchi lead into tiny air capillaries that intertwine with blood capillaries, where gases are exchanged.

"Inhaled air proceeds through two respiratory cycles that, together, consist of four steps. Most of the air inhaled in step 1 passes through the primary bronchi to the posterior air sacs…In step 2, the exhalation phase of this first breath, the inhaled air moves from the posterior air sacs into the lungs. There, oxygen and carbon dioxide (CO2) exchange takes place as inhaled air flows through the air-capillary system. The next time that the bird inhales, step 3, the oxygen-depleted air moves from the lungs into the anterior air sacs. The second and final exhalation, step 4, expels CO2-rich air from the anterior air sacs, bronchi, and trachea back into the atmosphere.

"This series of four steps maximizes contact of fresh air with the respiratory surfaces of the lung. Most importantly, a bird replaces nearly all the air in its lungs with each breath. No residual air is left in the lungs during the ventilation cycle of birds, as it is in mammals. By transferring more air and air higher in oxygen content during each breath, birds achieve a more efficient rate of gas exchange than do mammals…The air-sac system is an inconspicuous, but integral, part of the avian respiratory system…Air sacs are thin-walled (only one or two cell layers thick) structures that extend into the body cavity and into the wing and leg bones…The air sacs make possible the continuous, unidirectional, efficient flow of air through the lungs."

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