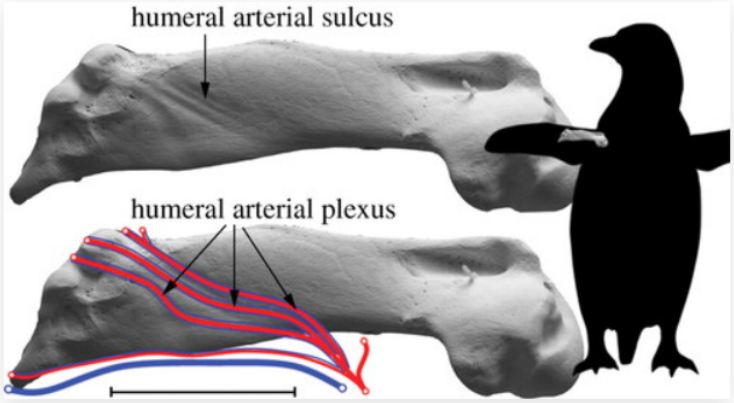
生物策略表

類別	生物策略 (Strategy)
生物策略 STRATEGY	翅膀減少熱量散失 (Wings Reduce Heat Loss)
生物系統 LIVING SYSTEM	企鵝 (Penguins)
功能類別 FUNCTIONS	#防止非生命威脅 #保護免受溫度影響 #Protect from non-living threats #Protect from temperature
作用機制標題	企鵝的翅膀透過血管設計形成逆流熱交換器，減少熱量損失。 (Wings of penguins reduce heat loss by forming a countercurrent heat exchanger via the vascular design.)
生物系統/作用機制示意圖 (確認版權、註明出處；畫質)	 https://royalsocietypublishing.org/doi/10.1098/rsbl.2010.0993

作用機制摘要說明 (SUMMARY OF FUNCTIONING MECHANISMS)

企鵝在冷水中覓食的主要適應是利用肱動脈叢，即通過鰭狀肢的血管逆流熱交換器（CCHE）。覓食時，企鵝暴露在遠低於核心體溫的水中，面臨持續的體溫過低威脅，部分透過管理沿著機翼的熱量流動來應對。

通常情況下，鳥類的翅膀由一條主要肱動脈供應血液，這條肱動脈橫穿肱骨。但企鵝的肱動脈分成三到五個主要血管，然後與兩根血管在肱骨-橈骨關節處的動脈吻合。每條肱動脈與兩條或更多的靜脈相連，形成逆流熱交換器，即肱動脈叢。

血液以核心體溫（38.5 攝氏度）供應到企鵝的機翼，流出的動脈血加熱進入較冷的靜脈血，熱量因此被儲存並返回到身體核心，而不是進一步傳播到冷水中。測量顯示企鵝肩部和翼尖之間高達 30 攝氏度的內部溫差，進一步證明瞭肱骨叢作為 CCHE 機制的功效。

The primary adaptation that allows penguins to forage in cold water is the utilization of the brachial artery bundle, also known as the counter-current heat exchanger (CCHE) located in their flipper-like limbs. While foraging, penguins are exposed to water temperatures much lower than their core body temperature, facing a persistent threat of hypothermia, partly mitigated by managing the flow of heat along the wings.

In most birds, the wings are typically supplied with blood by a single main brachial artery that crosses the humerus bone. However, in penguins, the brachial artery divides into three to five

main vessels, which then anastomose with two vessels at the humerus-radius joint. Each brachial artery is connected to two or more veins, forming a counter-current heat exchanger, known as the brachial artery bundle.
Blood, at a core body temperature of 38.5 degrees Celsius, is supplied to the wings of the penguin. The arterial blood, upon exiting, heats up the cooler venous blood, thereby storing heat and returning it to the body core, rather than dispersing it further into the cold water.
Measurements show an internal temperature difference of up to 30 degrees Celsius between the penguin's shoulder and wingtips, further demonstrating the effectiveness of the brachial artery bundle as a CCHE mechanism.

文獻引用 (REFERENCES)

「企鵝的體型通常小於預期的海洋恆溫動物的最小體型。對小藍企鵝（Eudyptula minor）的解剖觀察表明，現存的企鵝利用區域異溫積極地克服了較小的體型閾值。小藍企鵝的翼動脈形成肱動脈叢，這是一系列源自腋動脈的三條平行動脈（包括邊緣動脈），取代了一條肱動脈。神經叢的每條動脈都與至少兩條靜脈相連，形成逆流保溫系統。因此，肱骨叢限制熱量進入機翼遠端區域並消散到海水中，最終減少產熱和隔熱所需的體積質量。肱骨神經叢被證實是企鵝亞科的同源特徵，其中小企鵝的肱骨神經叢與非洲企鵝的肱骨神經叢最相似。肱骨叢代表了海洋恆溫動物體型最小值的漏洞，並提供了對現存企鵝生態的深入了解。」

「現存的企鵝翅膀經過高度改造，變成了一種堅硬的槳狀結構，配備了大大減少的固有翅膀肌肉，並且表現出任何現存鳥類群體中最低程度的固有關節活動性。」

“Penguins are generally smaller than the predicted minimum body size for marine endotherms. Anatomical observations of the little blue penguin (*Eudyptula minor*) suggest that extant penguins actively defeat the lower size threshold using regional heterothermy. The wing arteries in the little blue penguin form a humeral plexus, a series of three parallel arteries (including the marginal artery) that stem from the axillary artery, replacing a single brachial artery. Each artery of the plexus is associated with at least two veins to form a counter current heat-retention system. The humeral plexus thus restricts heat from entering distal areas of the wing and dissipating into seawater, ultimately reducing the bulk mass required for heat production and insulation. Humeral plexi are confirmed as a synapomorphic character of the Spheniscinae, with the humeral plexus of *E. minor* most similar to that of the African penguin *Spheniscus demersus*. The humeral plexus represents a loophole in body size minima of marine endotherms and offers insight into the ecology of living penguins.”(Daniel B. Thomas A B and R. Ewan Fordyce, 2007)

“Extant penguin wings are highly modified into a rigid paddle-like structure, equipped with greatly reduced intrinsic wing muscles, and exhibit the lowest degree of intrinsic joint mobility of any extant group of birds.” (Proc Natl Acad Sci U S A. 2007 Jul 10; 104(28): 11545–11550.)

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