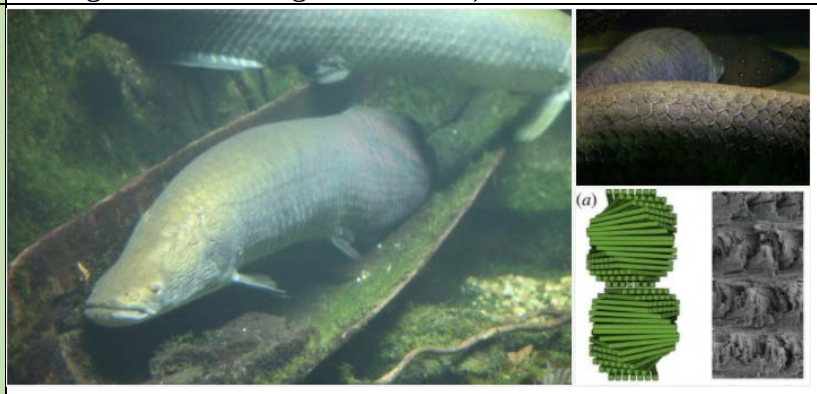
生物策略表

類別	生物策略 (Strategy)
生物策略 STRATEGY	亞馬遜魚類有堅韌的鱗片保護免受掠食者攻擊 (Amazonian fish has tough scales to protect from predators)
生物系統 LIVING SYSTEM	巨骨舌魚 *Arapaima gigas* (Arapaima fish)
功能類別 FUNCTIONS	#應付衝擊 #防止變形 #防止破裂/斷裂 #Manage impact #Prevent deformation #Prevent fracture/rupture
作用機制標題	巨骨舌魚的鱗片非常堅韌，是因為它們由排列成旋轉夾板結構的組織所構成 (Arapaima fish scales are extremely tough because they made of tissue arranged in the Bouligand structure)
生物系統/作用機制示意圖	

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

為了在食人魚 (piranha) 出沒的亞馬遜水域中存活，巨骨舌魚 (arapaima fish) 演化出像盔甲般的鱗片。這些鱗片分為兩層：堅硬外層可以用來保護免受飢餓掠食者的牙齒傷害；柔軟底層則有足夠的柔韌性，可以在發生攻擊時「回彈」(bounce back) 並回復其形狀。

這些鱗片的堅硬層和柔軟層共同作用，提供一個彈性 (resilient) 屏障，用以抵禦掠食者的攻擊而幾乎不受傷害，致使這些鱗片成為地球上最堅硬的構造之一。這些鱗片的秘密在於其內外兩層的連接方式。這鱗片內外兩層藉由膠原蛋白 (collagen) 連接，這是一種所有動物都有的結締組織。在人類中，皮膚中的膠原蛋白有助其維持緊緻與彈性。在巨骨舌魚的鱗片中，膠原蛋白以一種稱為旋轉夾板結構 (Bouligand structure) 的重要模式來連接堅硬的外層與柔軟的內層。這種結構也存在於龍蝦、甲蟲、及螃蟹的外殼中，是使這些外殼如此強固的關鍵。

旋轉夾板結構看起來像一道螺旋狀的階梯，具有以扭曲螺旋狀排列的纖維。巨骨舌魚的鱗片具有許多彼此相鄰排列的螺旋狀階梯。這種排列方式使鱗片強固、具有彈性、且抗裂。倘若食人魚攻擊不具這種鱗片的魚類，牠的牙齒將很容易穿裂其鱗片，使食人魚得以咬穿其下的柔軟魚體。然而，當巨骨舌魚遭受食人魚啃咬時，鱗片的旋轉夾板結

構可藉由將力通過這些「螺旋狀階梯」，來幫助分散來自牙齒的攻擊力。這般將攻擊力分散到更大區域有助魚減輕衝擊。在受到攻擊時，魚鱗上可能會出現小裂縫，但旋轉夾板結構可以阻止小裂縫繼續擴大到能被食人魚的牙齒穿透的程度。

「螺旋狀階梯」中膠原蛋白的排列是這種亞馬遜魚類的鱗片之所以堅韌難裂的原因。瞭解這種結構設計或能造就輕量裝甲材料的發明，用以防止爆炸，或作為更強固的汽車框架。

In order to survive in the piranha infested waters of the Amazon, the arapaima fish has evolved armor-like scales. The scales have two layers: A hard outer layer that protects from the teeth of hungry predators, and a soft underlayer that is flexible enough to “bounce back” and recover its shape if an attack occurs.

The hard and soft layers in the scales work together to provide a resilient barrier that can endure a predator attack with almost no damage, making these scales some of the toughest on Earth. The secret to these scales is in how these two layers are attached. The layers are connected by collagen, a connective tissue found in all animals. In humans, collagen in the skin helps it stay firm and elastic. In the arapaima fish scales, collagen connects the hard, outer layer to the soft inner layer in an important pattern called the Bouligand structure. This structure has also been found in the shells of lobsters, beetles, and crabs and is the key to what makes these shells so strong.

The Bouligand structure looks like a spiral staircase, with fibers arranged in a twisting, helical pattern. The arapaima fish scale has many of these spiral staircases arranged next to each other. This arrangement makes the scales strong, flexible, and resistant to cracking. If a piranha attacks a fish without scales like these, it’s teeth would easily crack its scales and allow the piranha to penetrate the soft body of the fish underneath. However when an arapaima fish is bitten by a piranha, the Bouligand structure helps distribute the attack from the teeth by allowing the force to travel through these “spiral staircases”. This spreads out the force of the attack over a larger area, helping to relieve the impact. During an attack, there may be a small crack in the fish scale, but the Bouligand structure keeps the small crack from growing large enough that the piranha’s teeth can break through.

The arrangement of the collagen in this ‘spiral staircase’ is the reason the Amazonian fish scales are so tough to crack. Understanding this design could lead to the invention of lightweight materials for armor that protects against explosions, or stronger frames for cars.

文獻引用 (REFERENCES)

「巨骨舌魚具有柔軟且交疊的圓鱗，是由強韌旋轉夾板結構排列的膠原蛋白基部層，以及礦化 (mineralized) 的堅硬外表層所組成，可保護其免受食人魚這種具有非常鋒利牙齒的掠食者的攻擊。」

「巨骨舌魚鱗片顯著較高的韌度似乎與其瓣層 (lamellae layers) 增厚以及鱗片厚度本身相關，此外也與更高的礦化度相關，這些特性都是保護在亞馬遜盆地中生活的巨骨舌魚免受食人魚攻擊所不可或缺的。」

"The arapaima has flexible and overlapping cycloid scales which consist of a tough Bouligand-type arrangement of collagen layers in the base and a hard external mineralized surface, protecting it from piranha, a predator with extremely sharp teeth."

"The significantly higher toughness of the arapaima scales appears to be associated with the increased thickness of their lamellae layers and scale thickness itself, and to a higher degree of mineralization, a necessity for protection of the arapaima from piranha attacks in the Amazon basin."

參考文獻清單與連結 (REFERENCE LIST)

Sherman, V. R., H. Quan, W. Yang, R. O. Ritchie, and M. A. Meyers. (2016). A comparative study of piscine defense: The scales of *Arapaima gigas*, *Latimeria chalumnae* and *Atractosteus spatula*. *Journal of the Mechanical Behavior of Biomedical Materials* 73: 1-16. (https://doi.org/10.1016/j.jmbbm.2016.10.001)

Yang, W., H. Quan, M. A. Meyers, and R. O. Ritchie. (2019). Arapaima fish scale: one of the toughest flexible biological materials. *Matter* 1: 1557-1566. (https://doi.org/10.1016/j.matt.2019.09.014)

延伸閱讀

生物系統延伸資訊連結 (LEARN MORE ABOUT THE LIVING SYSTEM/S)

https://en.wikipedia.org/wiki/arapaima_gigas
https://www.onezoom.org/life/@arapaima_gigas
https://eol.org/pages/204868

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AskNature 原文連結

https://asknature.org/strategy/amazonian-fish-has-tough-scales-to-protect-from-predators/