生物策略表

類別	生物策略 (Strategy)
生物策略 STRATEGY	鐵道蟲可發出多種色光（Railroad Worms Glow in Multiple Colors）
生物系統 LIVING SYSTEM	鐵道蟲 （Railroad worm）
功能類別 FUNCTIONS	#傳遞光訊號（可見光譜） #Send Light Signals in the Visible Spectrum
作用機制標題	位於鐵道蟲螢光素酶上的活性位，其大小可調控牠們所製造的螢光之能量高低，因而控制其顏色。（The sizes of the active sites on railroad worms' luciferase enzymes controls the energy level, and hence color, of the light they produce.）
生物系統/作用機制示意圖 (確認版權、註明出處；畫質)	 出處： https://dailybayonet.com/railroad-worms-emitting-red-light-working-details-explained-inside/

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

導言：

在月光下佈滿輕快飛舞光球的森林看似只是個源自童話故事的場景；然而，多虧了有些昆蟲體內的化學反應，它成為了真實存在世上的現象。雖然大部分的生物發光性甲蟲只會發出黃色或綠色的光芒，但其中一種被稱為鐵道蟲 (the railroad worm) 的甲蟲，也可製造出紅色的光。

策略：

鐵道蟲（*Phrixotrix hirtus*），一種原生於美州的螢火蟲 (firefly) 近親，沿其背部有著許多黃綠色的閃爍光點，使人憶起夜晚行駛列車上燈火通明的一扇扇窗子。從鐵道蟲頭部散發出的紅色光芒，不僅幫助牠們在黑暗中導航，亦可威嚇捕食者。就成蟲而言，雄性鐵道蟲會變化形體成甲蟲，而雌性則仍維持著可發光的蠕蟲形態。這個特性可幫助雄性在交配時順利定位出雌性的位置。

有趣的是，牠們已被發現可以調控自身散發光線的能力，當牠們受到干擾時，他們會發出更為強烈的光芒，亦可在不同的色光之間交替。

但，鐵道蟲究竟是如何創造出這場多彩的燈光秀？雖然生物發光現象（bioluminescence）可憑藉生物自身的化學反應或生物發光共生菌（bioluminescent symbiotic bacteria）的存在等兩種方式發生，然而鐵道蟲則只使用前者。一種被稱為螢光素酶（luciferase）的特化酵素具有一活性位（active site）可與螢光素（luciferin）分子結合。其分子結構的細微變化導致不同生物發光物種所發出的色光產生改變。

黃綠色螢光素酶具有較小的活性位，其意味著當螢光素與之結合時，會更緊密地壓縮，從而在兩分子之間產生可釋放高能光的靜電排斥現象（electrostatic repulsion），其放出

的高能光，被人類感知為綠色或黃色。在紅色螢光素酶的情況下，活性位較大且剛性較低，這導致螢光素酶與螢光素之間的靜電排斥減少。其產生的光能量亦較低，而被人類感知為紅色。

而這在能量上的差異為多少？由於紅光位於可見光譜的下端一方，紅色光子約發散 1.8 電子伏特的能量；相較而言，綠色光子則可散發 2.4 電子伏特的能量。

潛力：

醫學治療尋求以微創方式去定位和標靶體內的特定組織，而其中一種能達成這項要求的方式稱作生物成像（bioimaging）。使用光線和螢光，以及其他以外的工具，生物成像可應用於視覺化發生中的生物過程，或使 3D 成像的技術得以改進。

造成生物發光現象之甲蟲酶常應用於生物成像，而紅色酶在標靶特定組織時相當有用，這些組織通常會吸收或中和來自藍綠色光光譜的光線。在哺乳動物細胞中，像肌肉或血液這種富含血紅蛋白（hemoglobin）和肌紅蛋白（myoglobin）的組織便特別難成像，但若利用可製造紅光的酶，便可在生物技術應用中幫助標靶這些組織。

Introduction:

A moonlit forest filled with flitting balls of light may seem like a scene from a fairy tale, but it's a real-world phenomenon thanks to some insects' internal chemical reactions. While most bioluminescent beetles have a yellow or green glow, one, known as the railroad worm, also produces a red light.

The Strategy:

A close relative of fireflies and native to the Americas, railroad worms (*Phrixotrix hirtus*) have several yellow-green dots of light along their backs, bringing to mind the brightly lit windows of a train passing in the night. A red light is emitted from their heads, which helps them both to navigate in the dark and to intimidate predators. As adults, males morph into beetles, while the females remain in a glowing, worm-like state. This helps males locate females for reproduction.

Interestingly, they have been found to have control over their light-emitting powers, glowing more intensely when disturbed and alternating between colored glows.

But how, exactly, do they create this multicolored light show? Although bioluminescence can occur either through a chemical reaction of the creature's own, or through the presence of bioluminescent symbiotic bacteria, railroad worms use the former. A specialized enzyme known as luciferase has an active site to which a luciferin molecule binds. Subtle changes to the molecular structure alter the colored glow of different bioluminescent species.

Yellow-green luciferases have a smaller active site, which means that when the luciferin binds, it is more tightly compressed, creating an electrostatic repulsion between the two molecules that releases high-energy light, which we perceive as green or yellow. In the case of red luciferase, the active site is larger and less rigid, which leads to a reduction in the electrostatic repulsion

between the luciferin and the luciferase. The light produced is less energetic and is perceived as red.

Just how much of an energy difference is this? Red light is at the lower end of the visible spectrum, with red photons of light emitting about 1.8 electric volts of energy, compared to the 2.4 electric volts emitted by a green photon.

The Potential:
Medical treatments seek to locate and target specific tissues within the body in minimally invasive ways, and one method that allows for this is known as bioimaging. Using light and fluorescence, among other tools, it can be used to visualize biological processes as they occur, or to allow improved 3D imaging.

Beetle enzymes that produce bioluminescence are commonly used for bioimaging, and the red enzymes are highly useful for targeting tissues that typically absorb and neutralize lights in the blue-green spectrum. In mammalian cells, hemoglobin and myoglobin-rich tissues, like muscles and blood, are particularly difficult to image, but utilizing enzymes which produce red light could help target these tissues in biotechnological applications.

文獻引用 (REFERENCES)

「南美豎毛甲屬鐵道蟲（*Phrixotrix* railroad worms）的螢光素酶是唯一一種能自然催化發生在光譜紅色區域之生物發光現象的[OLE2]螢光素酶…
儘管他們的一級序列具相似性，南美豎毛甲屬的螢光素酶卻展示出顯著不同的理化性質。發散紅色的 PxRE 螢光素酶之活性位相較其他 PxGR 螢光素酶顯示出更高的受質親和性、催化效率及介電常數（dielectric constant）。此結果指出，PxRE 螢光素酶的螢光素結合位之苯並噻唑基（benzothiazolyl）側比 PxGR 螢光素酶更為緊密且更具極性。致突變作用（Mutagenesis）之相關研究則指出，在發散步驟中，螢光素結合位中噻唑基（thiazolyl）部分的差異可能是這些螢光素酶行生物發光現象時顏色相異的原因。」
(Viviani et al. 2006:467, 473)

「甲蟲螢光素酶使用相同的受質—D-螢光素（LH2）及 ATP 產生從綠色至紅色各不同顏色之生物發光現象。其中，鐵道蟲螢光素酶所發散的光，其顏色範圍最廣，包含綠色至紅色等顏色。甲蟲螢光素酶（尤其是螢火蟲螢光素酶）已被廣泛應用於生物分析，近期亦被使用於生物及病理過程的即時生物成像，包括如癌症或新藥之展望。發散遠紅外及近紅外線的螢光素酶因可應用於骨頭和富含血紅蛋白之組織的生物成像過程，亦被人類需要。」
(Bevilaqua et al. 2019: 1)

“The luciferases of the *Phrixotrix* railroad worms are the only [OLE2] luciferases that naturally catalyse bioluminescence in the red region of the spectrum…Despite the similarity of their primary sequences, the *Phrixotrix* luciferases display remarkably different physicochemical

properties. The active site of the red-emitting PxRE luciferase displays substrate affinities, catalytic efficiency, and a dielectric constant higher than those of the PxGR luciferase. These results suggest that the benzothiazolyl side of the luciferin-binding site of PxRE luciferase is tighter and more polar than that of PxGR luciferase. Mutagenesis studies suggest that differences in the thiazolyl portion of the luciferin binding site, during the emitting step, could be responsible for differences of bioluminescence colors in these luciferases." (Viviani et al. 2006:467, 473).

"Beetle luciferases produce bioluminescence of different colors from green to red using the same substrates, D-luciferin (LH2) and ATP. Among them, railroad worms luciferases emit light with the widest range of colors, ranging from green to red. Beetle luciferases, especially firefly ones, have been extensively used in bioanalysis, and more recently in real time bioimaging of biological and pathological processes, including cancer and prospection of new drugs. Far-red and near infra-red emitting luciferases are demanded for bioimaging such processes in bone and hemoglobin rich tissues." (Bevilaqua et al. 2019: 1)

參考文獻清單與連結 (REFERENCE LIST) **Harvard 或 APA 格式**

V.R. Viviani, F.G.C. Arnoldi, B. Venkatesh, A.J.S. Neto, F.G.T. Ogawa, A.T.L. Oehlmeyer, and Y. Ohmiya. (2006). Active-Site Properties of Phrixotrix Railroad Worm Green and Red Bioluminescence-Eliciting Luciferases. *The Journal of Biochemistry*.
(https://academic.oup.com/jb/article-abstract/140/4/467/761958?login=false)

V. R. Bevilaqua, T. Matsuhashi,G. Oliveira,P. S. L. Oliveira,T. Hirano, V. R. Viviani. (2019). Phrixotrixluciferase and 6′-aminoluciferins reveal a larger luciferin phenolate binding site and provide novel far-red combinations for bioimaging purposes. *Scientific Reports.* (https://www.nature.com/articles/s41598-019-44534-3)

延伸閱讀: Harvard 或 APA 格式（取自 AskNature 原文；若為翻譯者補充，請註明）

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

https://scitechdaily.com/railroad-worms-emit-red-light-now-scientists-finally-know-how-it-works/
https://dailybayonet.com/railroad-worms-emitting-red-light-working-details-explained-inside/
以上非 AskNature 的相關連結，屬相關資訊網址

撰寫/翻譯/編修者與日期

張翔鈞翻譯（2022/04/09）；許秋容編修 (2022/5/20)

AskNature 原文連結

https://asknature.org/strategy/railroad-worms-glow-in-multiple-colors/

更多補充的圖片 (1. 確認版權、註明出處　2. 品質: 盡量 72dpi 或 300K)

出處：https://speakzeasy.wordpress.com/tag/brazilian-railroad-worm/

解析度：300 dpi