1-11-3. DNA photochemistry

Overview

DNA photochemistry has advanced from the perspectives of oxidative damage, aging, and cancer suppression, and the advent of DNA origami technology has enabled the precise placement of photoactive molecules. In FRET, distance and orientation dependence, multistep energy transfer, and plasmon-enhanced emission have been demonstrated. In TTET, DNA damage and distance dependence have been analyzed, and single-molecule measurements of biomolecular dynamics have become possible. In electron transfer research, single-molecule studies have revealed pronounced heterogeneity in intramolecular electron transfer rates, greatly deepening our understanding of fundamental photochemical processes.

Current Status and Frontiers

DNA photochemistry is a research field that has long been investigated in detail, particularly regarding the intrinsic photochemical reactions of DNA that directly lead to oxidative damage, from medical and biological perspectives such as aging and cancer prevention. A unique feature of DNA as a research scaffold is that photoactive molecules can be introduced at arbitrary positions and orientations within its double-helical structure, which is not achievable in other molecular systems. Furthermore, since the advent of DNA origami technology in 2006, it has become possible to design sophisticated two-dimensional (2D) and three-dimensional (3D) DNA nanostructures and precisely arrange a wide variety of functional molecules within them. These advances have enabled researchers to use DNA as a molecular scaffold to integrate photoactive molecules in finely tuned spatial arrangements, thereby achieving precise control of intermolecular distance and orientation, and to analyze in detail fundamental photochemical processes such as energy transfer and electron transfer at the single-molecule level. This article introduces several representative examples of such developments.

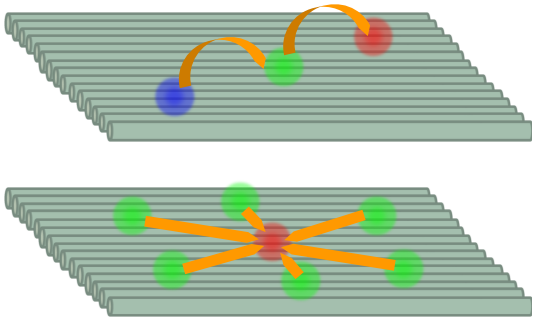

Figure 1. FRET on the 2D origami sheet.

1. Singlet–singlet energy transfer (Fluorescence resonance energy transfer: FRET)

FRET has been widely employed as a method for tracking nanoscale distance changes (ca. 1–10 nm) between two sites in biomolecules, owing to its strong dependence on intermolecular distance. By utilizing DNA, researchers were able to precisely control the distance and orientation of donor and acceptor molecules along the double helix, thereby clarifying the orientation dependence of FRET that had previously been difficult

to observe (Kashida, Asanuma et al.). Moreover, arranging fluorophores in regular patterns on 2D DNA origami structures enabled the observation of multistep energy transfer and demonstrated antenna effects proportional to the number of donor molecules. Additionally, when FRET pairs were positioned within plasmonic hotspots created by gold nanoparticles using 3D DNA origami structures, fluorescence emission rates and quantum yields were markedly enhanced, allowing FRET observation under conditions of 10 MHz photon emission (Tinnefeld et al.).

2. Triplet–triplet energy transfer (TTET)

When triplet photosensitizers arranged on DNA duplexes underwent TTET with molecular oxygen, singlet oxygen was generated, leading to helix-dependent DNA damage (Kanamori, Yuasa et al.). By placing triplet energy donors and acceptors at defined positions along the DNA double helix, the distance dependence of TTET was systematically analyzed (Wagenknecht et al.). Furthermore, by arranging a fluorescent donor and cyclooctatetraene acceptor through a single-stranded DNA scaffold, collision reaction dynamics could be exploited, enabling direct single-molecule measurements of biomolecular dynamics (Kawai et al.).

3. Electron transfer

From the late 1990s to the early 2010s, detailed investigations were conducted into electron transfer in DNA mediated by π-stacks, particularly focusing on the dependence of electron transfer rates on distance and sequence. More recently, these electron transfer processes have been directly observed using single-molecule techniques, revealing the mechanistic details of multistep electron transfer. These studies have highlighted that, even within the confined molecular environment of DNA, electron transfer rates exhibit significant heterogeneity, leading to new insights into electron transfer phenomena at the molecular scale (Kawai et al.).

References

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Future Perspectives and Directions

Looking ahead, it is anticipated that DNA nanostructures will serve as highly precise scaffolds for arranging photoactive molecules, enabling the integrated elucidation of single-molecule mechanisms of energy and electron transfer, and ultimately expanding toward applications in the understanding of biological functions and the development of advanced photonic devices.

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