COMMENTARY

Biomimetic attempts in electrochemiluminescence

Yue Cao,[1] Qingyuan Bao,[1] Yining Miao,[3] Wenlei Zhu,[2,*] and Yang Zhou[1,*]

[1]Institute of Advanced Materials, Nanjing University of Posts & Telecommunications, Nanjing 210023, China

[2]School of Environment, State Key Laboratory of Pollution Control and Resource Reuse, Nanjing University, Nanjing 210023, China

[3]Ivy Experimental School, Zhangjiagang 215600, China

*Correspondence: wenleizhu@nju.edu.cn(W.Z.); iamyangzhou@njupt.edu.cn(Y.Z.)

Received: July 24, 2023; Accepted: November 21, 2023; Published Online: November 22, 2023; https://doi.org/10.59717/j.xinn-mater.2023.100034

Citation: Cao Y., Bao Q., Miao Y., et al., (2023). Biomimetic attempts in electrochemiluminescence. The Innovation Materials **1(3)**, 100034.

Electrochemiluminescence (ECL) describes the phenomenon of light emission generated by chemical reactions between electro-triggered radicals of luminophores or coreactants. In this process, the electrical inputs are converted into optical readouts, and thus ECL inherits both advantages of electrochemistry and chemiluminescence (CL), such as no excitation light needed, excellent precision, wide dynamic range, simple instruments, etc. After the first detailed ECL research was reported in the mid-1960s by Hercules and Bard *et al.*, ECL is becoming a powerful analytical technology in modern era. Statistically, over 40,000 ECL instruments are in operation for clinical assays worldwide, generating hundreds of millions of dollars in sales per year. To some degree, ECL technology is an emerging biomedical diagnostic and versatile analytical tool following CL and fluorescence. The development of strong emission, elaborate sensing strategies, and new technologies are the three key areas of development in the ECL sensing domain.

Biomimicry stems from advances in biology and technical science, aiming to learn from nature and transform the world. The Greek words '*bios*' and '*mimetikos*' contribute to the term biomimetic, which was first used in chemistry for producing tough ceramic materials during the mid-1980s. The interesting question is, what will happen when biomimetic features are integrated with ECL technology? First, biomimetic catalysts or luminophores can achieve efficient charge injection, transferring, and recombination in the electro-redox process, leading to strong and stable ECL signals. Second, some unique bionic structures, such as biointerfaces with high biocompatibility, can inspire new ECL sensing strategies to achieve high-performance analysis in terms of sensitivity, accuracy, selectivity, etc. Third, bionics of biological processes can also lead to the development of new ECL sensing technologies. This commentary provides a brief overview of biomimetic attempts in these three areas of ECL research, using recent representative reports.

BIOMIMETIC CATALYTIC ECL EMISSION

ECL routes involve high-energy redox reactions, and catalysts (also known as co-reaction accelerators) can boost the ECL efficiency. Inspired by natural enzymes, Zhu's group designed Fe-based single-atom catalysts (SACs) with an FeN_4 coordination analogous to heme. The SACs exhibited enhanced oxygen reduction reaction (ORR) performance to produce reactive oxygen species (ROS; *e.g.*, $OH^{\bullet}$, $O_2^{\bullet-}$) for anodic luminol ECL.[1] To further guide the production of valuable intermediates, this group then regulated SACs' adjacent axial ligands, one crucial catalytic moiety of heme. A well-defined FeN_4 heme structure was anchored within N-rich graphene oxide featuring bioinspired axial coordination (Figure 1A). The axial ligand N atoms in Fe-based SACs selectively activate O_2, promoting O_2 binding and O-O bonds cleavage for selective generation of $OH^{\bullet}$, leading to strong cathodic luminol ECL. This method was eventually used to design biomimetic SACs-based immunosensing platform for the measurement of prostate-specific antigen with a low limit of detection (LOD) of 0.63 pg mL^{-1} and good recoveries of 94.34~108.34%.[2] Therefore, SACs can be designed with the single-atom coordination structure of natural enzymes, generating high ORR performance for ROS production, especially the four-electron reduction process. This operating principle can also guide the preparation of biological learning accelerators for other ORR-involved coreactant ECL systems beyond luminol.

BIOMIMETIC ECL SENSING STRATEGY

Because most ECL sensing processes occur at the solid-liquid interface, constructing biomimetic interfaces may confer unique analytical properties. Mussels are fouling organisms that can adhere to almost any surfaces due to their protein composition. Our group exploited Mussels adhesive protein-inspired polydopamine (PDA) as a thin, surface-adherent substrate through an oxidative self-polymerization method (Figure 1B). Then, a secondary reaction was introduced via Michael Addition for *in-situ* grafting of zwitterionic segments (3-dimethyl (methacryloyloxyethyl) ammonium propane sulfonate, DMAPS) and recognition elements (aptamer). The ECL biointerface exhibited an ultrathin, loose structure with unexpected robustness, likely due to the firm adhesion of PDA and covalent linkage. The neutrally charged DMAPS formed a strong hydration on the surface, providing resistance to fouling. Finally, this biomimetic ECL interface was incorporated into gas diffusion electrodes within a microfluidic reaction device, showing minimal fouling while maintaining high analytical performance in non-label checking and dynamics monitoring of exosomes (Exos) along with excellent LOD at 162 N mL^{-1}.[3]

The ability to identify and detect targets in complex biological environments is undoubtedly a key feature in future sensing systems. Inspired by natural ion channels, Jian *et al.* prepared an artificial *Janus* TiO_2 nanochannel membrane to separate/connect the sample cell and detection cell (Figure 1C). Target-triggered aptamers and pH/H_2O_2-responsive metal-organic frameworks (MOFs; MIL-100(Fe)) were installed as gates to block both two entrances. As target cytochrome C (CytC) opened the aptamer gate, the stimulator of glucose could pass through the nanochannel. At the other gate, glucose was oxidized by oxidase-mimetic Au nanoparticles (NPs) to accumulate H_2O_2, further degrading MOFs. The pre-enwrapped ECL probes of $Ru(dcbpy)_3^{2+}$ within the MIL-100(Fe) were released to give ECL signals. As such, the architecture based on artificial nanochannel membranes with two cascade gates could efficiently filtered out the target specimen from the complex biological matrix, achieving direct ECL sensing of 1.0 nM CytC in undiluted serum.[4] their biomimetic structure endows the surface or membrane with special functions that meet the increasingly challenging requirements of sensing strategies in practice.

BIOMIMETIC NEW ECL TECHNOLOGY

Additionally, biomimetics can open new dimensions for ECL technology. As a reference to the photosynthesis of thylakoid membrane in nature, our group designed a porous hetero-shell by orderly assembling of imine-linked covalent organic frameworks (COFs) on Fe_3O_4 NPs-decorated polymeric hollow graphitic carbon nitride (g-C_3N_4) nanospheres (Figure 1D). In this structure, the interlaced heterogeneous shells display a matching band-edge level, allowing their outer and inner surfaces to simulate the separated redox centers with increased photogenerated carriers. The porous structure provided the shell with permeability and ensured the facile shuttling of reactive substances. Thus, these robust scaffolds enabled remarkable visible-light-driven photodegradation of tetracycline (Tc). Moreover, due to the inherent ECL attributes of g-C_3N_4 and the quenching effect of Tc, this artificial "membrane" has unique biomimetic self-responsiveness for Tc sensing, showing a low LOD of 0.031 μg L^{-1}. On this basis, our group proposed a novel ECL technology for *in-situ* evaluation of photodegradation processes in a homemade microreaction cell. This work offers new perspectives for using biomimetics technique to develop ways to simultaneously monitor and degrade an actual sewage.[5] Although ECL technology has made significant commercial advances in clinical diagnosis, it remains limited in other practical applications. However, it is possible to develop multifunctional nanomaterials to implement new ECL technology with reference to biophysiological processes, rather than just a certain structure.

CONCLUSION AND PERSPECTIVE

This commentary highlights three main aspects of ECL sensing through several recent reports. First, biomimetics can guide the design of efficient coreactant accelerators, such as mimetic enzymes. Second, smart sensing strategies can mimic natural process or phenomena, such as the construction of artificial interfaces and nanochannels. Third, biomimetics can extend

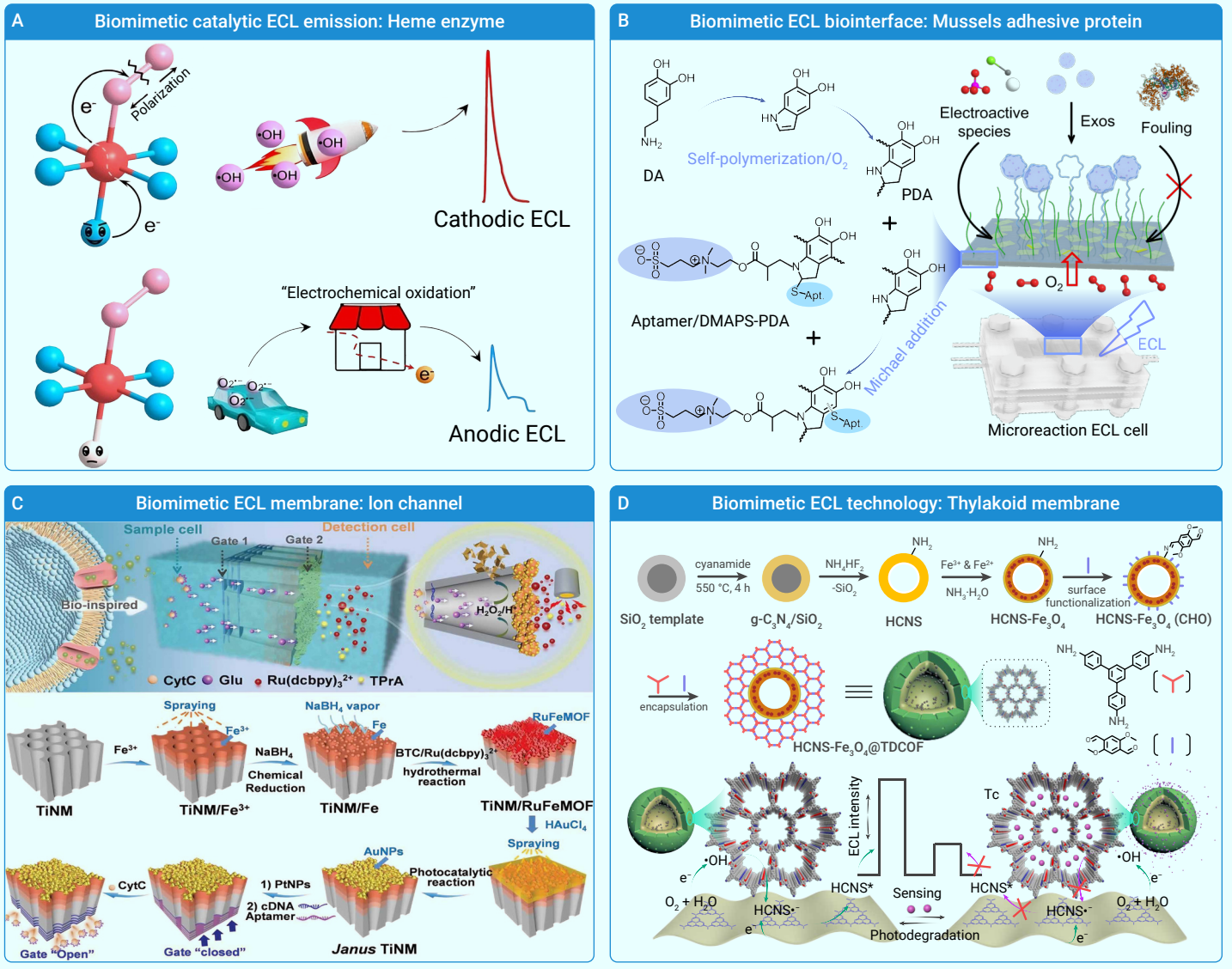

Figure 1. Biomimetic attempts in ECL sensing applications (A) Heme-inspired SACs for adjustable luminol ECL. Reprinted with permission from ref.[2], Wiley-VCH. (B) Mussels adhesive protein-inspired PDA as a platform for grafting zwitterionic DMAPS and aptamer to establish the ECL biointerface. Reprinted with permission from ref.[3], Wiley-VCH. (C) Ion channel-inspired nanochannels with two cascade gates for the ECL detection of CytC. Reprinted with permission from ref.[4], Wiley-VCH. (D) Photosynthetic thylakoid membrane-like hollow organic nano-scaffolds for the simultaneous treatment and sensing of Tc. Reprinted with permission from ref.[5], Wiley-VCH.

ECL to interdisciplinary research for spawning new technologies, that is, for example, the *in-situ* photocatalysis evaluation of low-abundance targets. While the concept of bionics has not yet gained popularity in ECL, it has the potential to inject new vitality into this classical ECL realm. Of course, the three aspects discussed above are not exhaustive of all the benefits of biomimetics. For instance, the ECL transducers are the core of the sensors, but their biomimetic features or structures have not yet been reported. As for the ECL biosensing system, biocompatibility is important to maintain biological activities and improve specific biometric recognition. The establishment of a biomimetic surface could potentially meet this demand. Mechanically robust and self-healing biomimetic materials are capable of adapting to changes in the complex environment, endowing the ECL sensors with reliable stability, and even the competence to regenerate and reuse. Last but not least, advanced bio-inspired ECL sensing technology needs to learn from nature and beyond. It is necessary to break through key techniques such as structure and function characterization of biomaterials to reveal the inherent law of excellent performance of typical biomaterials.

REFERENCES

1. Gu, W., Wang, H., Jiao, L., et al. (2020). Single-atom iron boosts electrochemiluminescence. Angew. Chem. Int. Ed. **59**: 3534–3538. DOI: 10.1002/anie.201914643.
2. Xu, W., Wu, Y., Wang, X., et al. (2023). Bioinspired single-atom sites enable efficient oxygen activation for switching anodic/cathodic electrochemiluminescence. Angew. Chem. Int. Ed. **62**: e202304625. DOI: 10.1002/anie.202304625.
3. Cao, Y., Wang, J.-X., Lin, C., et al. (2023). Zwitterionic electrochemiluminescence biointerface contributes to label - free monitoring of exosomes dynamics in a fluidic microreaction device. Adv. Funct. Mater. **33**: 2214294. DOI: 10.1002/adfm.202214294.
4. Jian, X., Xu, J., Guo, J., et al. (2023). Cascade-gates guarded asymmetrical nanochannel membrane: An interference-free device for straightforward detection of trace biomarker in undiluted serum. Small **19**: 2205995. DOI: 10.1002/smll.202205995.
5. Cao, Y., Wu, R., Zhou, Y., et al. (2022). A bioinspired photocatalysis and electrochemiluminescence scaffold for simultaneous degradation and in situ evaluation. Adv. Funct. Mater. **32**: 2203005. DOI: 10.1002/adfm.202203005.

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (22276100, 22304086), and the Start-Up Fund from NJUPT (NY221006, NY223051). The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.