



Cite this: *Analyst*, 2023, **148**, 806

Os(II/III) complex supports pH-insensitive electrochemical DNA-based sensing with superior operational stability than the benchmark methylene blue reporter†

Miguel Aller Pellitero, ^a Nandini Kundu, ^b Jonathan Szczepanski ^b and Netzahualcóyotl Arroyo-Currás ^{*a,c}

DNA-based electrochemical sensors use redox reporters to transduce affinity events into electrical currents. Ideally, such reporters must be electrochemically reversible, chemically stable for thousands of redox cycles, and tolerant to changing chemical environments. Here we report the first use of an Os(II/III) complex in DNA-based sensors, which undergoes pH-insensitive electron transfer with 35% better operational stability relative to the benchmark methylene blue, making it a promising reporter for continuous molecular monitoring applications where pH fluctuates with time.

Received 20th November 2022,
Accepted 4th January 2023

DOI: 10.1039/d2an01901a

rsc.li/analyst

Introduction

Electrochemical, DNA-based (E-DNA) sensors rely on binding/hybridization-induced conformational changes to generate an electrical signal, enabling single-point¹ or continuous² molecular measurements. Electrochemical, aptamer-based (E-AB) sensors represent a specific type of E-DNA sensors that enable the continuous and real-time monitoring of molecular targets.³ For simplicity, and given their ability to support continuous measurements, this work focuses on E-AB sensors as a model system. E-AB sensors consist of mixed monolayers of blocking alkylthiols and alkylthiol-modified aptamers self-assembled onto gold electrodes, and a redox reporter attached to the terminal end of the aptamers (Fig. 1A). These aptamers are designed to undergo rapid and reversible binding-induced conformational changes that affect electron transfer kinetics from the redox reporter in a way easily measurable *via* electrochemical methods (Fig. 1B),⁴ thus enabling the continuous monitoring of targets. Moreover, the target-induced conformational switching in E-AB sensors readily allows sensing *in vivo*,⁵ while also minimizing the effect of spurious non-specific binding to the aptamers themselves. Given these

characteristics, E-AB sensors represent an unparalleled platform for continuous molecular sensing.⁶

Despite their unique characteristics, however, the field of application of E-AB sensors is limited by two main drawbacks. First, E-AB sensors undergo rapid signal loss upon continuous electrochemical interrogation, especially when deployed in biological fluids.⁷ And second, the strong dependency of their signaling output on pH limits their use to pH-regulated environments. Seeking to address the first problem, several studies have focused on different elements of the sensing layer like the chemical nature of the blocking alkylthiol^{8,9} or the DNA strands,¹⁰ the technique used for sensor interrogation,^{11,12} and the electrode material.¹³ However, the second problem has received significantly less attention. Seventeen years after the first report on this technology,³ most published E-AB sensors still rely on the use of a single redox reporter which undergoes pH-dependent electron transfer: methylene blue (MB).^{14,15}

Alternative redox reporters such as anthraquinone or ferrocene have been used for the fabrication of E-AB sensors; however, these reporters are not suitable for continuous monitoring applications. On the one hand, anthraquinone presents a formal redox potential of $E_{\text{AQ}}^{\text{ox}} \sim -0.50$ V vs. Ag/AgCl,^{16,17} which overlaps with the reduction of molecular oxygen, making the electrochemical response of this reporter oxygen concentration-dependent. In addition, at such voltages the hydrogen peroxide generated by the electrochemical reduction of oxygen¹⁸ can compromise the stability of the monolayer. On the other hand, the product of the oxidation of ferrocene ($E_{\text{Fc}}^{\text{ox}} \sim +0.25$ V), the ferrocenium ion, undergoes ligand exchange reactions with chloride ions naturally present in bio-

^aDepartment of Pharmacology and Molecular Sciences, Johns Hopkins University School of Medicine, Baltimore, Maryland, 21205, USA. E-mail: netzarroyo@jhmi.edu; Tel: +1 (443) 287-4798

^bDepartment of Chemistry, Texas A&M University, College Station, TX 77843, USA

^cDepartment of Chemical and Biomolecular Engineering, Johns Hopkins University, Baltimore, Maryland, 21218, USA

† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d2an01901a>



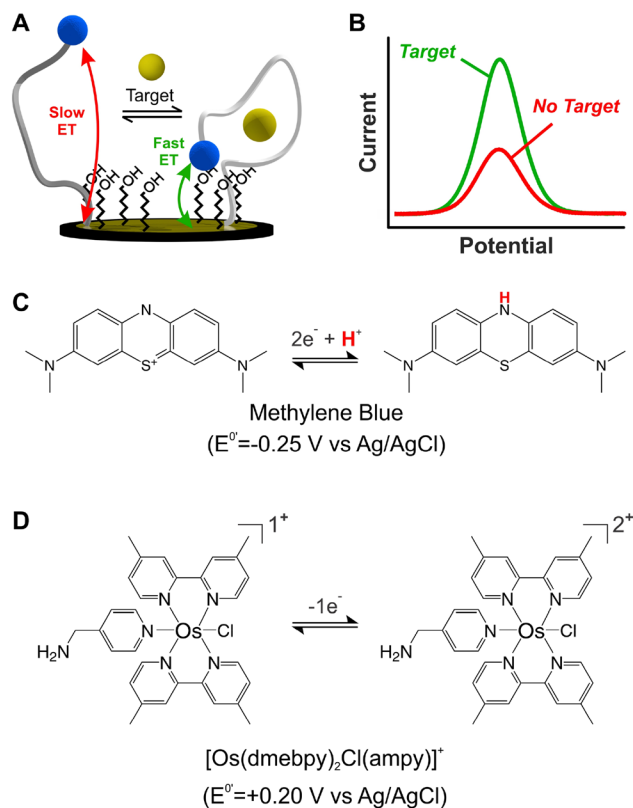


Fig. 1 DNA-based electrochemical sensors use redox reporters to convert affinity events to electrical currents. (A) Anatomy and working principle of electrochemical, aptamer-based (E-AB) sensors, which are used in this study as a model system. (B) In the presence of target, aptamers undergo binding-induced conformational changes that alter the electron transfer rate of the redox reporter with the electrode. These changes can be monitored *via* square wave voltammetry. (C) State-of-the-art E-AB sensors rely on methylene blue (MB) as redox reporter, which undergoes the exchange of 2 electrons and 1 proton. (D) In contrast, $[\text{Os}(\text{dmeppy})_2\text{Cl}(\text{lampy})]^+$ only exchanges 1 electron and is not proton concentration-dependent.

logical media, leading to fast current loss.^{19,20} Moreover, the positive voltages required for ferrocene oxidation overlap with the beginning of surface oxidation of gold, also compromising the monolayer. Only recently, Li *et al.* published a novel reporter based on tetrathiafulvalene that has a positive formal reduction potential, $E_{\text{TF}}^{\text{O}'} \sim +0.05$ V, and undergoes pH-independent electron transfer.²¹ However, the radical-based mechanism of electron transfer in this molecule may promote secondary chemical reactions with species present in commonly used buffers as well as biomolecules present in biological fluids such as serum or blood, limiting its ability to support long-term sensor operation. Further studies are needed to conclusively determine the value of this reporter for continuous molecular monitoring.

The sole availability of MB as a stable reporter has prevented potential applications of E-AB sensors in biomedical platforms. For example, the electrochemistry of MB is strongly pH-dependent (Fig. 1C), not allowing reliable use in

unbuffered matrices such as sweat, saliva, or other time-changing, non-biological environments.⁶ In addition, and similarly to anthraquinone-based sensors, the negative voltage window necessary to enable MB electron transfer (-0.1 V to -0.5 V vs. Ag/AgCl) promotes the loss of thiol-based monolayer elements from gold surfaces.²² Seeking to address these issues, here we assess the suitability of an Os(II/III) organometallic complex, $[\text{Os}(\text{dmeby})_2\text{Cl}(\text{ampy})]^+$ (Fig. 1D), to act as redox reporter for E-AB and other E-DNA platforms. While other Os complexes have been used for decades in enzyme-based sensors,^{23–26} and some of them are commercially used for continuous glucose monitoring,²⁷ $[\text{Os}(\text{dmeby})_2\text{Cl}(\text{ampy})]^+$ has never been used in E-DNA platforms. Additionally, previous examples of Os-based complexes in DNA-based systems use chemically labile and toxic compounds.^{28,29} In contrast, our reporter is not labile and uses Os(II/III) oxidation states, which are nontoxic and already commercially approved for use in glucose monitoring, thus offering a clear translational path for incorporation into molecular monitors.

Materials and methods

Chemicals and materials

Ammonium hexachloroosmate(IV) ((NH₄)₂OsCl₆), ammonium hexafluorophosphate (NH₄PF₆), 4-(aminomethyl)pyridine (ampy), 4,4'-dimethyl-2,2-dipyridil (dmebpy), tris(2-carboxyethyl)phosphine (TCEP), *N*-(3-dimethylaminopropyl)-*N'*-ethylcarbodiimide hydrochloride (EDC), guanidine hydrochloride (GC), procaine hydrochloride, *N,N*-dimethylformamide (DMF), ethylene glycol (EG), diethyl ether, methanol, ethanol, 11-mercaptopundecanoic acid (MUA), and 6-mercapto-1-hexanol (MCH) were purchased from Sigma-Aldrich (St Louis, MO, USA). Phosphate buffer saline (PBS, 11.9 mM HPO₃²⁻, 137 mM NaCl, 2.7 mM KCl; pH 7.4), magnesium chloride hexahydrate (MgCl₂·6H₂O), sodium chloride (NaCl) sulfuric acid (H₂SO₄), sodium hydroxide (NaOH), and new methylene blue (NMB) were purchased from Fisher Scientific (Waltham, MA, USA). Tobramycin sulfate was purchased from Spectrum Chemical (New Brunswick, NJ, USA). Gold working (cat. #002314, Ø = 1.6 mm) and platinum counter electrodes (cat. #012961) were purchased from ALS (Tokyo, Japan). Ag/AgCl (1 M KCl) reference electrodes (CHI111) and a multichannel potentiostat (CHI1040C) were purchased from CH Instruments (Austin, TX, USA). Silicon carbide grinding paper (36-08-1200) was purchased from Buehler (Lake Bluff, IL, USA). Cloth pads (MF-1040) and alumina slurry (CF-1050) were purchased from BASi (West Lafayette, IN, USA). The DNA sequences used for the fabrication of E-AB sensors are listed below:

Name	Sequence	Manufacturer
Tobramycin-COOH	5' [COOH-C10] GG GAC TTG GTT TAG GTA ATG AGT CCC [C6-S-S] 3'	Biosyn (Lewisville, TX, USA)
Procaine-COOH	5' [COOH-C10] GAC AAG GAA ATC CTT CAA CGA AGT GGG [C6-S-S] 3'	Biosyn (Lewisville, TX, USA)

The synthesis of $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$ was based on previously reported protocols.^{30,31} However, in this work, we substituted the bipyridyl ligands for dmebpy to decrease the redox potential of the final complex, ensuring that it falls within a voltage window below the surface oxidation of gold (<0.3 V vs. Ag/AgCl).³² The synthesis of this complex involves two straightforward steps (Fig. S1, ESI[†]). First, we reacted 200 mg of $(\text{NH}_4)_2\text{OsCl}_6$ with 180 mg dmebpy in 5 mL of DMF under reflux and N_2 atmosphere for 1 hour. After cooling down the mixture for 30 min, the product was filtered to separate the NH_4Cl precipitate, and 3 mL of MeOH was added to the mixture. Then, 200 mL of diethyl ether was slowly added under vigorous stirring, causing the precipitation of the intermediate complex $(\text{Os}(\text{dmebpy})_2\text{Cl})\text{Cl}$. This complex was isolated by vacuum filtering and washed with diethyl ether. In the second step, 200 mg of the $(\text{Os}(\text{dmebpy})_2\text{Cl})\text{Cl}$ were reacted with 40 mg of ampy in 5 mL of ethylene glycol under reflux and N_2 atmosphere for 3 hours. After cooling down the product to 25 °C for 1 hour, 5 mL of a saturated NH_4PF_6 aqueous solution was slowly added to the mixture while vigorously stirring, observing the precipitation of $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]\text{PF}_6$ (dark solid). The final product was vacuum filtered, washed with deionized water, and air-dried overnight at 25 °C. For both steps, we obtained yields higher than 85%.

Gold electrodes were polished using silicon carbide grinding paper and a cloth pad with alumina slurry, and then rinsed with water and sonicated for 1 min to remove polishing debris. The freshly polished electrodes were electrochemically activated by serially scanning *via* cyclic voltammetry, first from -0.3 to -1.6 V in 0.5 M NaOH, then from 0 to 1.6 V in 0.5 M H_2SO_4 , a total of two hundred cycles each at a scan rate of 0.5 V s^{-1} . After this process, the electrodes were ready for DNA functionalization. Unless otherwise stated, all square wave voltammograms in this work were measured using a square wave amplitude of 75 mV and a voltage step of 1 mV. The square wave frequency varied as indicated in figure panels and captions. Cyclic voltammograms were measured using a scan rate of 5 V s^{-1} and a voltage step of 1 mV. All voltammetric measurements are reported relative to the Ag/AgCl (1 M KCl) reference electrode.

For monolayer experiments, freshly polished and activated electrodes were incubated in 1 μ M solutions of MUA prepared in ethanol for 2 hours at 25 $^{\circ}$ C. This dilute concentration pre-

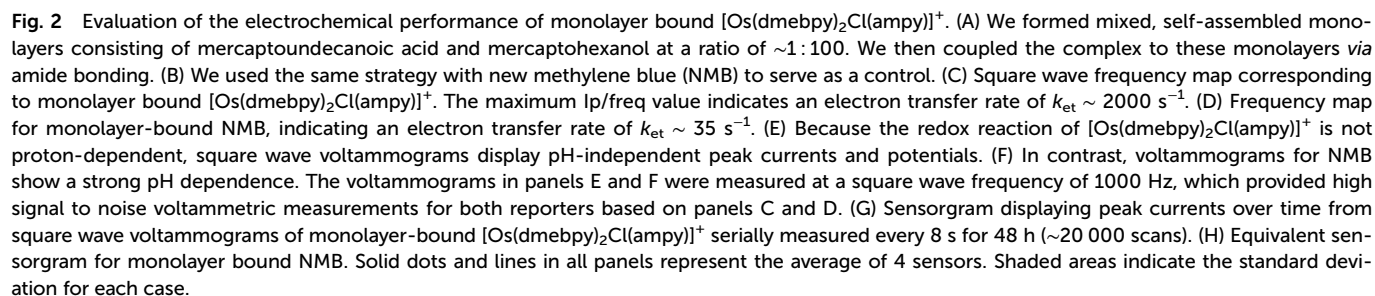
vented the effect of unreacted, free carboxylic groups on the sensors electrochemical response at different pH values. Then, the redox reporter, either NMB or the Os complex, was chemically bound to the surface *via* EDC chemistry (Fig. S2†). For this step, electrodes were incubated in a 30 mM EDC solution containing 5 mM of MgCl_2 , 150 mM of NaCl, and 100 μM of the redox reporter for 3 hours under constant stirring using a Thermomixer (1500 rpm). Controls were prepared incubating the electrodes in the same solution in the absence of EDC. After the coupling reaction, electrodes were rinsed with water and then with two separate washes for 30 min each under vigorous stirring using the Thermomixer. The first wash used acetonitrile containing 1 M of H_2SO_4 . The second wash used 6 M guanidinium chloride solution prepared in ethanol:water (v/v 4 : 1). These washes were critical to remove non-specifically bound redox reporter molecules from electrode surfaces, particularly in the case of the highly insoluble osmium complex (Fig. S3, ESI†). Last, electrodes were incubated overnight at 25 °C in 10 mM MCH.

1 μL of either procaine or tobramycin aptamer solutions at a 100 μM concentration were treated with 2 μL of a 5 mM TCEP solution for 1 h. Then, freshly polished and activated electrodes were immersed in 2 μM solutions of the aptamer prepared in PBS for 4 h. After rinsing with water, electrodes were incubated overnight in EDC solutions containing the redox reporter, as indicated above. After the coupling reaction, electrodes were rinsed with water and washed in acetonitrile and guanidinium chloride solutions. Last, electrodes were incubated in 10 mM MCH solutions for 2 h under vigorous stirring. After rinsing with water, sensors were ready for use. In contrast to most E-AB sensors, the aptamer sequences provided by the manufacturer and used in this work had a COOH^- modification at the 5' end, which we used to attach the redox reporter. We evaluated if the position of MB and alkanethiol moieties influenced the performance of tobramycin aptamers, observing minimal differences (Fig. S4, ESI †). However, as reported by Chamorro and colleagues,³³ other sequences including procaine-binding aptamers are affected by the surface orientation of aptamer molecules.^{10,12}

Two different hybridization assays were demonstrated in this work. For the first, we challenged [Os(dmebpy)₂Cl(ampy)]⁺-modified sensors made using the tobramycin-binding aptamer with saturating concentrations (10 μM) of fully complementary DNA strands prepared in PBS, and measured the change in voltammetric peak currents as a function of time. The second assay consisted of the attachment of pre-hybridized duplex DNA to the gold electrodes. For this, we mixed 1 μL of a tobramycin aptamer solution prepared at a concentration of 100 μM with 2 μL of TCEP for 1 hour. Then, this solution was mixed with 2 μL of a 100 μM solution of the complementary strand, progressively increasing the temperature up to 85 °C and kept the solution there for 30 min. After this, the temperature was

Because electron transfer from $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$ does not involve the exchange of protons with the media (Fig. 1D), it is pH insensitive. To evaluate this effect, we measured voltammograms of the surface-bound reporter in PBS first adjusted to pH = 7.4, and then titrated either down to pH = 4.0 and 6.0, or up to pH = 9.0. Given the ability of the complex to undergo electron transfer regardless of proton concentration, we obtained voltammograms with peak currents and peak potentials within the standard deviation of the batch (shaded areas in Fig. 2E). In contrast, voltammograms measured from

Surface-bound $[\text{Os}(\text{dmeppy})_2\text{Cl}(\text{ampy})]^+$ complexes undergo reversible electron transfer at rates that are fifty times faster than NMB. We illustrate this by showing frequency maps built from square wave voltammograms for each reporter (Fig. 2C and D). Briefly, we interrogated the modified electrodes *via* square wave voltammetry across a range of frequencies and cal-



Specifically, when we challenged the sensors with saturating concentrations of the drug (1 mM), we observed square wave frequency-dependent “signal-ON” and “signal-OFF” responses that are characteristic of E-AB sensors (Fig. 3B and C, Fig. S5, ESI†).^{5,37} We also observed this behavior in NMB-functionalized sensors (Fig. 3E–G); however, the frequencies required to observe the two responses in Os-based sensors were approximately 70-fold larger in magnitude than those

This journal is © The Royal Society of Chemistry 2023

A second consideration to explain the worse signaling performance of $[\text{Os}(\text{dmebpv})_2\text{Cl}(\text{ampy})]^+$ is that its electron transfer rate may be too fast to measure target binding to the aptamer under conditions of thermodynamic equilibrium. Specifically, the conformation dynamics of nucleic acids typically fluctuate with time constants of a few nanoseconds.³⁸ Such time constants are expected to slow down for surface-bound oligos because of changes in persistence length and folding degrees of freedom to slower time constants, potentially to periods of microseconds. At the optimal square wave frequency for signal-ON interrogation of the $[\text{Os}(\text{dmebpv})_2\text{Cl}(\text{ampy})]^+$ -modified aptamer (14 500 Hz in Fig. 3C), current is being sampled every 70 μs , a time constant that may be approaching the folding rates of surface bound oligos. Although this is speculation, similar effects (lower gain) have been observed with ferrocene-modified aptamers.³⁷ Ferrocene is another redox reporter that undergoes electron transfer at rates much faster than NMB (and MB). More research beyond the scope of this work is needed to gain further insight into this question.

A

Current / μ A

Potential / V

1500Hz

Target

No Target

B

% Signal

[Procaine] / M

C

Current / μ A

Potential / V

700Hz

No Target

Target

D

% Signal

[Procaine] / M

Analyst, 2023, **148**, 806–813 | 811

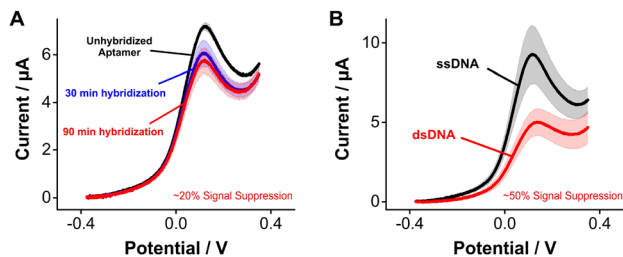


Fig. 5 $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$ supports sensing of nucleic acid hybridization events. (A) Voltammograms from a 26 nucleotide-long, electrode-bound tobramycin aptamer functionalized with the osmium-based reporter at $t = 0$, $t = 30$ min, and $t = 90$ min after exposure to a $10 \mu\text{M}$ solution of fully complementary strands. (B) Control voltammograms for non-hybridized sensors (black), and sensors that were fabricated after pre-hybridizing the aptamer with its complement for 1 h. Voltammograms were measured using a square wave frequency of 1800 Hz , as determined from frequency maps based on best peak current signal-to-noise ratios. Lines and dots represent the average of 4 sensors. Shaded areas represent their standard deviation.

Seeking to highlight the versatility of $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$ as a reporter for other DNA-based platforms beyond E-AB sensors, we evaluated its use for DNA hybridization assays. Upon hybridization, the redox reporter moves away from the electrode surface, which decreases its freedom of movement and, therefore, its electron transfer rate.⁴ For such measurements, we challenged electrode-bound tobramycin aptamers with saturating concentrations of fully complementary strands. Hybridization of the strands repositions the reporter further away from the electrode surface, leading to a decrease in voltammetric peak currents of $\sim 20\%$ after 90 min of incubation in complement strands (Fig. 5A). This effect was not observed when challenging the same sensors with control, non-complementary strands (Fig. S10, ESI†). We observed larger signal differences when we prepared pre-hybridized DNA duplexes of the tobramycin aptamer plus its complement in solution, and then formed sensor monolayers using the duplexes. In this case, duplex-functionalized sensors presented a decrease of $\sim 50\%$ in voltammetric currents relative to unhybridized E-AB sensors (Fig. 5B). The lower signal gain observed between the real-time measurement (Fig. 5A) and the pre-hybridization experiment (Fig. 5B) could be explained by the slow hybridization kinetics induced by the larger size and hydrophobic nature of $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$. Nevertheless, these results indicate that the complex can support signaling across different DNA-based sensing platforms, and that future optimization of aptamer-reporter coupling strategies may significantly improve the signaling output of $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$ -modified sensors.

Conclusions

We report the first use of $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$ as a redox reporter for E-DNA sensors. This complex can be efficiently coupled to mixed self-assembled monolayers of mercaptoun-

decanoic acid in mercaptohexanol *via* EDC chemistry and undergoes reversible and pH-insensitive electron transfer at rates that are fifty times faster than the benchmark methylene blue reporter used in E-DNA sensors. Additionally, Os-modified sensor monolayers are 35% more stable under continuous voltammetric interrogation than methylene blue-modified analogs. In a similar way, this Os complex can also be coupled to surface-bound nucleic acid aptamers to enable aptamer-based electrochemical sensing, also enabling the electrochemical monitoring of hybridization events. However, the hydrophobic nature of $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$ poses the challenge of non-specific adsorption on sensor surfaces when attached to surface-bound aptamers post monolayer formation. Future efforts from our group will focus on developing phosphoramidite-coupled $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$ for the bottom-up incorporation of the complex to oligonucleotide strands during solid phase synthesis. This approach should eliminate non-specific binding of bulk $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$ molecules to sensor surfaces while simultaneously allowing for targeted and highly efficient coupling to aptamers. Finally, the relevance of ultrafast electron transfer to E-DNA sensing is still to be demonstrated; however, the ability to probe sensor surfaces at the sub millisecond scales enabled by $[\text{Os}(\text{dmebpy})_2\text{Cl}(\text{ampy})]^+$ may open the door for the real-time study of ultra-fast biological processes *in vivo*, such as rapid neuronal firing in the brain.

Author contributions

M. A. P. and N. A. C. contributed equally to research work conceptualization, data curation, formal analysis, methodology and manuscript writing. M. A. P. performed the investigation, data analysis and image processing. N. A. C. acquired the funding, supervised the work, and administered the project.

Conflicts of interest

The authors report no conflicts of interest.

Acknowledgements

This study was supported by the National Institute of General Medical Sciences of the National Institutes of Health under Award Number R01GM140143. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

References

- 1 A. Victorious, Z. Zhang, D. Chang, R. Maclachlan, R. Pandey, J. Xia, J. Gu, T. Hoare, L. Soleymani and Y. Li, *Angew. Chem., Int. Ed.*, 2022, **61**, e202204252.



- 2 J. Das, S. Gomis, J. B. Chen, H. Yousefi, S. Ahmed, A. Mahmud, W. Zhou, E. H. Sargent and S. O. Kelley, *Nat. Chem.*, 2021, **13**, 428–434.
- 3 Y. Xiao, A. A. Lubin, A. J. Heeger and K. W. Plaxco, *Angew. Chem., Int. Ed.*, 2005, **44**, 5456–5459.
- 4 M. A. Pellitero, A. Shaver and N. Arroyo-Currás, *J. Electrochem. Soc.*, 2019, **167**, 037529.
- 5 N. Arroyo-Currás, J. Somerson, P. A. Vieira, K. L. Ploense, T. E. Kippin and K. W. Plaxco, *Proc. Natl. Acad. Sci. U. S. A.*, 2017, **114**, 645–650.
- 6 N. Arroyo-Currás, P. Dauphin-Ducharme, K. Scida and J. L. Chávez, *Anal. Methods*, 2020, **12**, 1288–1310.
- 7 A. Shaver and N. Arroyo-Currás, *Curr. Opin. Electrochem.*, 2022, **32**, 100902.
- 8 A. Shaver, S. D. Curtis and N. Arroyo-Currás, *ACS Appl. Mater. Interfaces*, 2020, **12**, 11214–11223.
- 9 Z. Watkins, A. Karajić, T. Young, R. White and J. Heikenfeld, *ChemRxiv*, 2022, This content is a preprint and has not been peer-reviewed.
- 10 A. Shaver, N. Kundu, B. E. Young, P. A. Vieira, J. T. Szczepanski and N. Arroyo-Currás, *Langmuir*, 2021, **37**, 5213–5221.
- 11 N. Arroyo-Currás, P. Dauphin-Ducharme, G. Ortega, K. L. Ploense, T. E. Kippin and K. W. Plaxco, *ACS Sens.*, 2018, **3**, 360–366.
- 12 M. A. Pellitero, S. D. Curtis and N. Arroyo-Currás, *ACS Sens.*, 2021, **6**, 1199–1207.
- 13 M. A. Pellitero and N. Arroyo-Currás, *Anal. Bioanal. Chem.*, 2022, **414**, 5627–5641.
- 14 V. Clark, K. Waters, B. Orsburn, N. N. Bumpus, N. Kundu, J. T. Szczepanski, P. Ray and N. Arroyo-Currás, *Angew. Chem., Int. Ed.*, 2022, e202211292.
- 15 S. Lin, X. Cheng, J. Zhu, B. Wang, D. Jelinek, Y. Zhao, T.-Y. Wu, A. Horrillo, J. Tan, J. Yeung, W. Yan, S. Forman, H. A. Coller, C. Milla and S. Emaminejad, *Sci. Adv.*, 2022, **8**, eabq4539.
- 16 D. Kang, R. J. White, F. Xia, X. Zuo, A. Vallée-Bélisle and K. W. Plaxco, *NPG Asia Mater.*, 2012, **4**, e1–e1.
- 17 Y. Liu, Y. Liu, Z. Matharu, A. Rahimian and A. Revzin, *Biosens. Bioelectron.*, 2015, **64**, 43–50.
- 18 J. C. Fornaciari, L.-C. Weng, S. M. Alia, C. Zhan, T. A. Pham, A. T. Bell, T. Ogitsu, N. Danilovic and A. Z. Weber, *Electrochim. Acta*, 2022, **405**, 139810.
- 19 D. Kang, F. Ricci, R. J. White and K. W. Plaxco, *Anal. Chem.*, 2016, **88**, 10452–10458.
- 20 A. Singh, D. R. Chowdhury and A. Paul, *Analyst*, 2014, **139**, 5747–5754.
- 21 S. Li, A. Ferrer-Ruiz, J. Dai, J. Ramos-Soriano, X. Du, M. Zhu, W. Zhang, Y. Wang, M. Á. Herranz, L. Jing, Z. Zhang, H. Li, F. Xia and N. Martín, *Chem. Sci.*, 2022, **13**, 8813–8820.
- 22 K. K. Leung, A. M. Downs, G. Ortega, M. Kurnik and K. W. Plaxco, *ACS Sens.*, 2021, **6**, 3340–3347.
- 23 T. J. Ohara, R. Rajagopalan and A. Heller, *Anal. Chem.*, 1993, **65**, 3512–3517.
- 24 R. Kumar and D. Leech, *J. Electrochem. Soc.*, 2014, **161**, H3005.
- 25 E. Tremey, C. Stines-Chaumeil, S. Gounel and N. Mano, *ChemElectroChem*, 2017, **4**, 2520–2526.
- 26 M. Marquitan, A. Ruff, M. Bramini, S. Herlitze, M. D. Mark and W. Schuhmann, *Bioelectrochemistry*, 2020, **133**, 107487.
- 27 G. McGarraugh, *Diabetes Technol. Ther.*, 2009, **11**, S-17–S-24.
- 28 E. Paleček and M. A. Hung, *Anal. Biochem.*, 1983, **132**, 236–242.
- 29 M. Fojta, P. Kostečka, M. Trefulka, L. Havran and E. Paleček, *Anal. Chem.*, 2007, **79**, 1022–1029.
- 30 F. P. Dwyer, H. A. Goodwin and E. C. Gyarfas, *Aust. J. Chem.*, 1963, **16**, 42–50.
- 31 A. M. Ricci, E. J. Calvo, S. Martin and R. J. Nichols, *J. Am. Chem. Soc.*, 2010, **132**, 2494–2495.
- 32 A. Ricci, C. Rolli, S. Rothacher, L. Baraldo, C. Bonazzola, E. J. Calvo, N. Tognalli and A. Fainstein, *J. Solid State Electrochem.*, 2007, **11**, 1511–1520.
- 33 A. Chamorro-Garcia, G. Ortega, D. Mariottini, J. Green, F. Ricci and K. W. Plaxco, *Chem. Commun.*, 2021, **57**, 11693–11696.
- 34 V. Mirceski, R. Gulaboski, M. Lovric, I. Bogeski, R. Kappel and M. Hoth, *Electroanalysis*, 2013, **25**, 2411–2422.
- 35 B. Wang, W. Ke, J. Guang, G. Chen, L. Yin, S. Deng, Q. He, Y. Liu, T. He, R. Zheng, Y. Jiang, X. Zhang, T. Li, G. Luan, H. D. Lu, M. Zhang, X. Zhang and Y. Shu, *Front. Cell. Neurosci.*, 2016, **10**, 239.
- 36 A. Y. Satoh, J. E. Trosko and S. J. Masten, *Environ. Sci. Technol.*, 2007, **41**, 2881–2887.
- 37 P. Dauphin-Ducharme and K. W. Plaxco, *Anal. Chem.*, 2016, **88**, 11654–11662.
- 38 H. Ma, C. Wan, A. Wu and A. H. Zewail, *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**, 712–716.

