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Development of Smartphone-based ECL Sensor for Dopamine Detection: Practical Approaches

Hyun J. Kwon
Andrews University, hkwon@andrews.edu

Elmer Rivera
Andrews University, elmeralbertocr@gmail.com

Mabio R. Cohelo Neto
Andrews University, mabioc@andrews.edu

Daniel Marsh
Andrews University

Jonathan Swerdlow
Andrews University, swerdloj@andrews.edu

See next page for additional authors

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Development of smartphone-based ECL sensor for dopamine detection: Practical approaches

Hyun J. Kwon [a,*], Elmer Ccopa Rivera [a], Mabio R.C. Neto [a], Daniel Marsh [a], Jonathan J. Swerdlow [b], Rodney L. Summerscales [b], Padma P. Tadi Uppala [c]

[a] Department of Engineering, Andrews University, Berrien Springs, MI 49104, United States of America
[b] Department of Computing, Andrews University, Berrien Springs, MI 49104, United States of America
[c] School of Population Health, Nutrition & Wellness, Andrews University, Berrien Springs, MI 49104, United States of America

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ABSTRACT

In this work, a compact, mobile phone-based ECL sensor apparatus was developed using the phone cameras, screen-printed electrodes (SPE), and mobile app for dopamine detection. Methods of DC voltage application for ECL reaction were comprehensively studied from the mobile phone itself or external power. Under optimized sensing conditions, with disposable carbon SPE and 20 mM coreactant tri-*n*-propylamine (TPrA), acceptable repeatability and reproducibility were achieved in terms of relative standard deviation (RSD) of intra- and interassays, which were 6.7 and 5.5%, respectively. The biochemical compound dopamine was measured due to its ECL quenching characteristics and its clinical importance. The quenching mechanism of $Ru(bpy)_3^{2+}$/TPrA by dopamine was investigated based on the estimation of the constants of the Stern-Volmer equations. The linear range for detectable dopamine concentration was from 1.0 to 50 μM ($R^2 = 0.982$). As the developed mobile phone-based ECL sensor is simple, small and assembled from low-cost components, it offers new opportunities for the development of inexpensive analytical methods and compact sensors.

1. Introduction

Electrochemiluminescence (ECL) is an electrochemical process in which molecules undergo electron–transfer reactions on an electrode surfaces to form an excited, photon emitting state. The emitted light is detected on the sensor when triggered by a required voltage. ECL offers great advantages over fluorescence-based detection [1]; ECL allows high signal-to-noise measurement because ECL does not require an excitation light source and thus background noise due to scattered light is reduced. ECL is a highly localized and time-triggered detection method since ECL signal generating reactions will only take place on the electrode for the duration of an applied potential. In addition, because it requires only a voltage to trigger the reaction, instrumentation can be minimized. Currently ECL is a powerful analytical technique used in many areas, ranging from fundamental studies to practical applications such as pharmaceutical analysis, immunoassays, clinical diagnosis and environmental analysis, among others [2–4]. The ECL system based on the inorganic compound tris(2,2′-bipyridine)ruthenium(II) ($Ru(bpy)_3^{2+}$) has been widely used in many ECL studies [5,6]. This dye was found to be robust in presence of adequate coreactants, leading to high emission with different voltage dependent mechanisms. When the coreactant is in excess, the ECL intensity is positively related to the concentration of $Ru(bpy)_3^{2+}$ [5].

The current golden standard of ECL detectors is the photomultiplier tube (PMT). PMT provides high sensitivity but is expensive, requires a high voltage input (~1500 V) and also requires a complete light shield. Recent reports indicated that photodiode could be a good alternative to PMT for the detection of the ECL response of the $Ru(bpy)_3^{2+}$ system [7,8]. Because the $Ru(bpy)_3^{2+}$ based ECL signal is in the visible light range (~620 nm), it is also visible to the naked eye and consumer cameras. It has been proven that the signal detected by a cell phone camera is well correlated with the PMT data [9].

Delaney and Hogan [9] and Delaney et al. [10] successfully implemented a mobile phone camera as an ECL detector and demonstrated the validity of its results compared to those from PMT; however, these reports showed rather limited detection limits, and no actual target molecules were in place. The traditional ECL detection was performed through the combination of expensive benchtop potentiostats and PMT detectors. In this context, the ubiquitous cell phone can change the PMT driven instrumentation for ECL sensors. The advantage of this approach is that cell phones could provide the control over the cell phone camera and ECL sensor through the use of a mobile app. Current cell phones have powerful processors for the storage and analysis of imaging data and are usually equipped with powerful data transmission capabilities [11]. In addition, the camera is readily available in mobile

* Corresponding author.
E-mail address: hkwon@andrews.edu (H.J. Kwon).

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phones without needing additional detectors, and it could allow monitoring of spatial distribution of the ECL emission within the electrode geometry, providing additional valuable information. These characteristics would make it possible for the mobile phone-based ECL apparatus to be easily implemented in low-resource setting.

Dopamine is selected as a target molecule for its importance in clinical tests and simplicity/straightforwardness in ECL investigation. Dopamine is a catecholamine that affects numerous physiological processes. It plays an important role in the functioning of the central nervous, cardiovascular, renal, immune, and hormonal systems, as well as in drug addiction and Parkinson's disease [12,13]. Due to its clinical significance, sensitive and reliable determination of dopamine is important in research and clinical disease diagnosis. To date, various types of electrochemical sensors have been developed due to its active electrochemical nature [14]. Detection in ECL is based on quenching of ECL through an energy transfer [15,16]. A report with an electrochemical sensor with graphene modified electrode claimed that it had a linear range of 1 μM–15 μM with a detection limit of 0.27 μM [17]. Liu et al. [15] showed linear ranges of 50 nM – 50 μM using ECL sensor with CdTe Quantum Dots and 3.7 μM–450 μM with near infrared quantum dot-based ECL.

In this work, ECL quenching based dopamine detection using a compact, mobile phone-based ECL sensor apparatus has been explored. Sensing conditions were optimized to provide sufficient signal intensities for the cell phone camera. To the best knowledge of authors, this is the first study that detects a biochemical compound using a Ru $(bpy)_3^{2+}$/Tri-*n*-propylamine (TPrA) system and simple carbon SPE in a self-contained, cell phone camera based ECL sensor. Time series data from cameras were obtained and analyzed for better understanding of the quenching mechanisms.

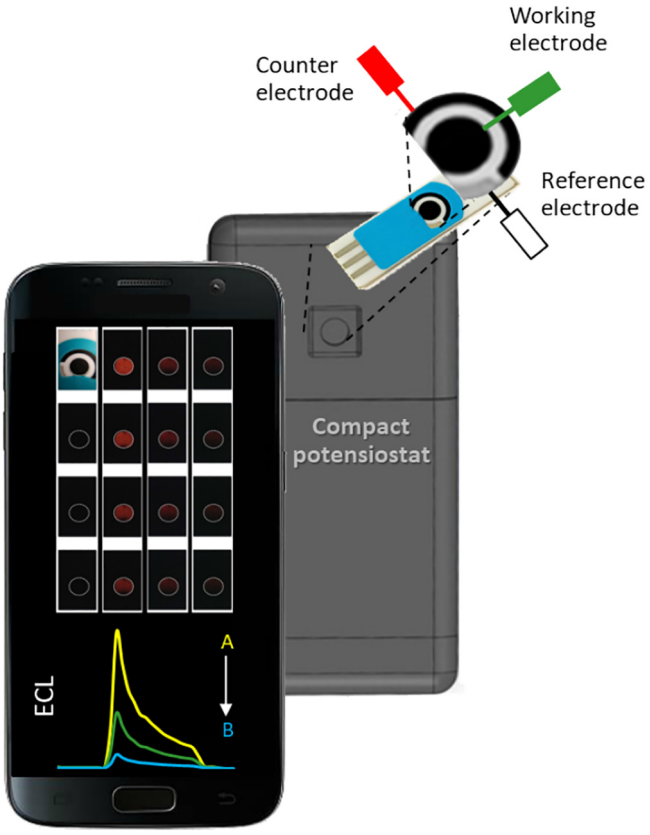

Fig. 1. Scheme of the proposed mobile phone-based ECL sensor apparatus.

2. Materials and methods

2.1. Chemicals and reagents

Tris (2,2′-bipyridyl) dichlororuthenium (II) hexahydrate ($Ru(bpy)_3Cl_2{\cdot}6H_2O$) and coreactants of tri-*n*-propylamine (TPrA), dibutylaminoethanol (DBAE) were purchased from Sigma Aldrich (now Millipore Sigma). Sodium dodecyl sulfate (SDS), Triton-X, 2,2,2-tetrafluoroethanol (TFE), dopamine hydrochloride were also purchased from Millipore Sigma. N-(3-aminopropyl)diethanolamine (APDEA) was purchases from Tokyo Chemical Industry Co. Ltd. The supporting electrolyte phosphate buffer solutions (PBS) were prepared by dissolving PBS tablets (Sigma) in water (pH 7.4). All aqueous solutions were prepared with Milli-Q water purchased from APS Water (resistivity ≥ 18.2 MΩ cm).

2.2. Apparatus

A schematic of the proposed mobile phone-based ECL sensor apparatus is shown in Fig. 1. It consists of a mobile phone (Samsung Galaxy S7) and a custom, compact potentiostat, which was modified from the open source Rodeostat circuit board (IO Rodeo). The cell phone camera is aligned with the hole of the container to fit the mobile phone camera and placed just above the working electrode. The custom potentiostat is connected on one side with the cell phone and the screen-printed electrodes (SPEs) on the other side. The container ensures light shielding, and a mobile app controlled the voltage application and camera control. All experiments were carried out with disposable SPEs that were purchased from the DropSens (Metrohm AG). The reference electrode was an Ag/AgCl electrode, and the working electrode (radius of 2 mm) was a carbon paste electrode in most experiments. Gold, platinum, or nanoparticle modified carbon SPEs were also tested to evaluate electrode effects.

2.3. ECL measurements

For each measurement, 50 μl of sample was applied to the disposable SPE to cover the working and reference electrode. The ECL reaction was triggered by applying specified voltage to the working, reference and/or counter electrode unless specified otherwise. The ECL measurements were recorded by the Samsung Galaxy S7 model cellular phone. This is not the latest model; however, this model was used because this study was targeting low resource setting where the most updated technology is not available. Cell phone cameras were set to pro mode with autofocus mode at ISO 3200, and burst mode was used to collect image sequences with frame per second (FPS) of 8–20.

A mobile app was developed to control the voltage application, capture the images, and analyze the image sequences. The mobile app sends out a signal to initiate the voltage application through a potentiostat, while simultaneously collecting images taken from the built-in digital camera. Then, the mobile app identifies the region of interest from the image sequences and analyzes the signal intensity by converting the CMOS data to RGB. Results from the app were compared to the results from ImageJ software with the time series plug-in (open source image processing software) for verification. The average signal intensities over the region of interest were plotted as a function of time. All measurements were performed at room temperature and each data points are average results of three measurements.

2.4. Dopamine sample preparation

Dopamine was freshly prepared and the time passed was recorded as it degraded with time. After 3 h, the sample was discarded. Stock solution of 50 mM dopamine was first prepared in 0.1 M PBS and it was diluted to final dopamine concentrations of 1.0, 5.0, 10, 20, 50 μM in 0.1 M PBS with 5 μM $Ru(bpy)_3^{2+}$ and 20 mM TPrA.

3. Results and discussion

3.1. Electrical hardware design

ECL reaction requires a simple voltage excitation to initiate the reaction. In this study, the optimal voltage excitation method that can be controlled and/or provided by the cell phones was explored. First, two-electrode based DC voltage application methods were investigated. The advantages of the two-electrode based excitation system are that it is simple and the power can be driven from the cell phone directly. Nevertheless, due to the inherent voltage drop at the electrode interface in the two electrodes system, it requires higher voltage of 2–3 V to initiate the reaction. The AC voltage, derived from an audio jack of a mobile phone, can be rectified to provide DC voltages to the two electrodes. However, usually it measures at 0.5 V RMS (AC) from the audio jack, so it needs amplification. A full wave DC amplification circuits was generated to rectify and amplify at the same time. The amplified voltage (6–10 V) was sufficient to manipulate it in the range of 1–3 V through a voltage divider; however, the series of capacitors used in the amplification circuit caused a time delay. The ECL signal was significantly delayed as shown in Fig. 2A compared to that from DC power supply. Another way to provide DC directly from the mobile device is using USB charging port, without the need for the rectification circuit. The latest mobile phones may not have an audio jack, but newer USB ports are capable of sending power in either direction. A simple adaptor (micro USB to USB) and charging cable (USB to micro USB) allows power to be redistributed as an output source at ~5 V. However, the USB charge port has current limitation at 0.5 mA. Compared to the results of higher currents (2.0 and 5.0 mA), a current as low as 0.5 mA at the same voltage applied compromises the reaction kinetics significantly as shown in Fig. 2B. These results demonstrated the importance of power capacity in choosing the right DC power input. Additional challenge arises when using the power from the USB port: It is difficult to develop and customize due to the default manufacturer setting. With the two-electrode system, the power driven from the cell phone can be applied directly via audio jack or USB charging port; however, this approach has limitations in practical application and customization.

Next, voltage application via a potentiostat-based three-electrode system was studied. The open source potentiostat circuit schematics was adopted and modified to generate a custom potentiostat, and manipulate the allowable maximum current setting (12 mA). The ECL sensing results with the custom potentiostat were compared to those with the CHInstrument potentiostat by applying a chronoamperometry type of voltage source to the sample of the $Ru(bpy)_3^{2+}$/TPrA system (5 μM $Ru(bpy)_3^{2+}$ and 20 mM TPrA in 0.1 M PBS). With the custom potentiostat, the ECL reaction was triggered at 1.2 V [18]. The best sensing result was obtained with the 12 mA setting of the custom potentiostat. This confirms the importance of using the maximum current setting even at the same DC voltage setting. The results suggest that the 12 mA setting was the best to trigger the strongest reaction at lower voltages. It is advantageous to choose lower voltage applications because high voltages can cause unwanted bubbles or heating of the fluid on the electrode. Table 1 summarizes advantages and disadvantages of the various methods in the two and three-electrode system. Taken together, the three-electrode system with the custom potentiostat and current limit setting of 12 mA produced reliable signals. This approach was used to study the ECL quenching by dopamine.

3.2. Disposable screen-printed electrode (SPE): Material and waiting time effects on ECL response

Electrode material is critical in electron transfer for the ECL reaction. The strong dependence of ECL efficiency on electrode material supports the contribution of direct oxidation of TPrA. Zu and Bard [19] showed that the carbon, gold and platinum working electrodes were used for ECL experiments and produced significant signals. The SPEs provide the convenience of not having to clean the surface after each use; however, the quality of commercially purchased SPEs might have been compromised due to screen-printing inks and polymeric binders [20]. In this study, the sensing performance of SPEs of gold, carbon, and platinum as working electrodes were investigated on the $Ru(bpy)_3^{2+}$/TPrA system (5 μM $Ru(bpy)_3^{2+}$ and 20 mM TPrA in 0.1 M PBS). As shown in Fig. 3A, without any pretreatment of the SPEs, significant ECL signals were produced only with the carbon SPEs, and little signals were observed with gold and platinum SPEs at the same conditions. Reports with permanent gold or platinum electrodes claimed that they could provide higher ECL intensity by promoting surface electron transfer [19]. Little signal with the commercial gold and platinum SPE could be attributed to the insufficient contact between nanoparticles and the interference of binding material that was used to plate a thin layer of electrode in the SPE production [20]. Gold and platinum SPE could be further treated with UV ozone, annealing or polishing to improve the electric conductance; however, this is beyond the scope of this work and needs to be separately investigated. The carbon electrode is working without any extra step of annealing or cleaning, making it ideal for a variety of application. Therefore, carbon electrodes were used for subsequent ECL experiments.

Waiting time before measurement also affects the ECL signal. Martinez-Olmos [21] reported that the signal through luminol in SPE becomes stronger with longer waiting time. This behavior was also observed with the ECL setup where the disposable SPEs were used. When the sample was first applied, the carbon electrode created huge contact resistance in the electrode. It is attributed that, with the waiting time, the solution gets into the microstructure of the electrode and makes it "wet", creating less contact resistance. Fig. 3B shows that concentrations of $Ru(bpy)_3^{2+}$ as low as 200 nM were measurable with the new carbon

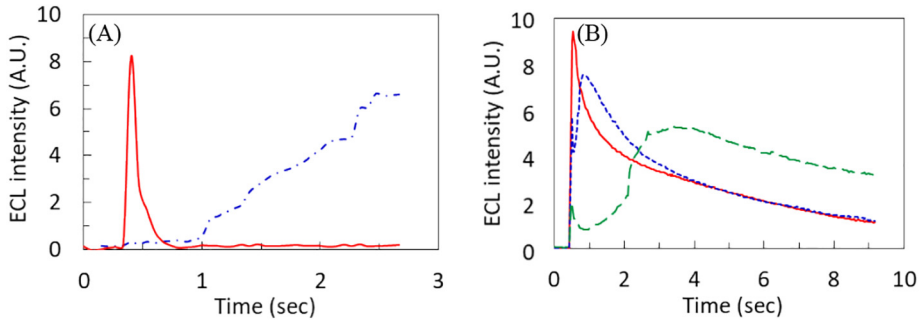

Fig. 2. A) ECL intensity with stable power source from a DC power supply (solid line) and the effect of amplifying rectifier circuit (dotdash line); B) ECL intensity with DC power supply at current of 0.5 mA (dashed line), 2.0 mA (solid line) and 5.0 mA (dotted line).

Table 1
Advantages and disadvantages of two-electrode and three-electrode systems for electrical hardware design.

	Two-electrode system			Three-electrode system
	Audio jack -rectification only	Audio jack - rectification with amplification	Direct USB	Potentiostat
Advantages	• Simple, no time delay. • Powered by cell phone directly.	• Simple. • Powered by cell phone directly.	• Simple. • Powered by cell phone directly.	• Holds the voltage steady. • Controlled by app.
Disadvantages	• Due to the voltage drop, it may not have sufficient triggering voltage. • Voltages may vary. • Requires higher voltage.	• Significant time delay. • Requires higher voltage.	• Altered kinetics due to the limiting current. • Requires higher voltage. • Hard to customize.	• Complex. • Additional DC power source required.

SPEs after the waiting time, and the reused SPEs did not need the waiting time.

3.3. Reproducibility and repeatability of the mobile phone-based ECL sensor

The repeatability within the same sensor unit was evaluated by testing the $Ru(bpy)_3^{2+}$/TPrA system system for five triplicate experiments. The relative standard deviation (RSD) was calculated to each experiment at the maximum ECL intensity peak to describe its intra-assay variation. The mean of the individual RSDs was defined as the intra-assay RSD, which was calculated to be 6.7%.

The reproducibility in a different sensor unit was evaluated by monitoring the precision of results between different experiments ($n = 5$) for the $Ru(bpy)_3^{2+}$/TPrA system (5 μM $Ru(bpy)_3^{2+}$ and 20 mM TPrA in 0.1 M PBS). It was expressed by the inter-assay RSD, which was 5.5%. The standard deviation of the mean ECL intensity throughout the reaction is shown in Fig. 3C. The inter-assay RSD was calculated at maximum peak by dividing the standard deviation by the mean.

The inter-phone sensor variability is an important parameter; however, it is beyond the scope of this study. The rapid evolution of the mobile technology makes it difficult to develop a standard platform that works on a variety of phones. Nevertheless, the ECL sensor offers a unique advantage in that the measurement is performed in a controlled lighting condition, focus, and angle, in addition to the consistent digital camera settings to make it easier to adapt for various phone models. The mobile app and the measurement apparatus need to be slightly modified to optimally interface with different models. This study focuses on a fundamental study of developing the mobile phone based ECL apparatus for detection of dopamine or phenolic compounds.

3.4. Determination of coreactant-based ECL assays

The electrochemical signals from $Ru(bpy)_3^{2+}$ are relatively low; however, the recent development of co-reactants makes it possible to enhance the signal for naked-eye detection [6]. The effect of coreactants was tested as the coreactant amplification of ECL emission is critical. Coreactants TPrA, DBAE, and APDEA 20 mM were separately applied to 1.0 μM $Ru(bpy)_3^{2+}$ on the carbon SPE, and the results are shown in Fig. 3D. Among these, TPrA showed the strongest signal intensity with fast onset kinetics. DBAE also showed a visible signal that is sufficient for camera detection; however, it shows slower reaction kinetics. APDEA also altered the reaction kinetics and showed very slow onset reaction kinetics. The aforementioned results indicated that ECL emission with the TPrA coreactant provided amplification of ECL signal to be

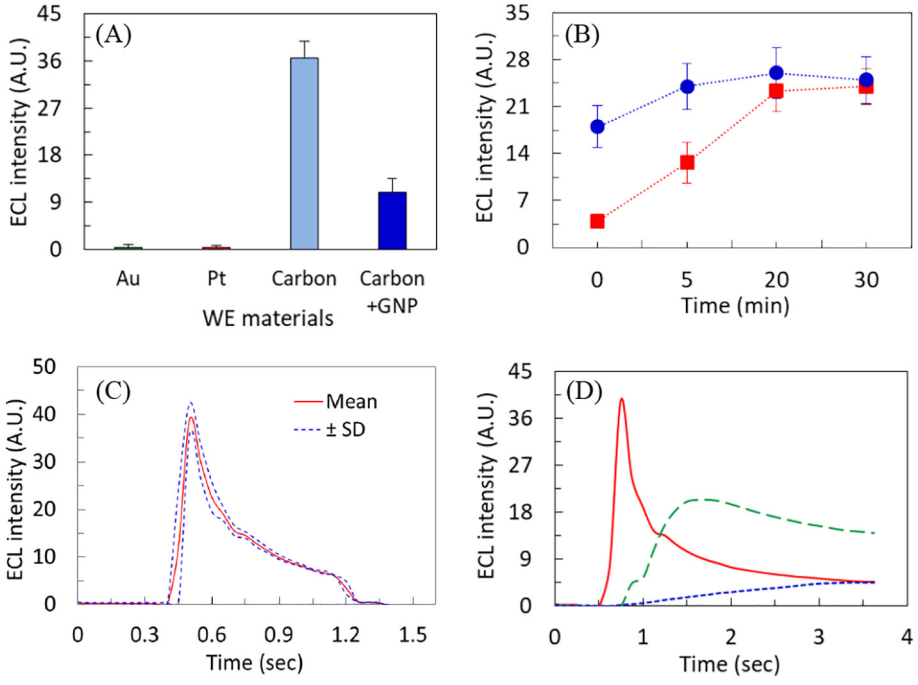

Fig. 3. A) Performance of SPEs of gold, carbon, and platinum as working electrodes on the $Ru(bpy)_3^{2+}$/TPrA system; B) Waiting time effect on new (square symbol) and reused (circle symbol) carbon SPEs; C) Standard deviation of the mean of the ECL intensity to describe the variation of the measurements of different experiments; D) Effect of applied different co-reactants, APDEA (dotted line), DBAE (dashed line), TprA (solid line) on the $Ru(bpy)_3^{2+}$/TPrA system with a carbon SPE. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

detected by the current mobile phone cameras. The emission spectrum of ECL with $Ru(bpy)_3^{2+}$/TrPA on a glassy carbon electrode ranges from 550 to 750 nm with the maximum peak at 620 nm [22]. In this study, the concentration of TPrA was fixed at 20 mM, which is in good agreement with maximum ECL response obtained by previous report [22].

3.5. Application on ECL quenching by dopamine

The ECL quenching assays by dopamine were performed with 5 μM $Ru(bpy)_3^{2+}$ and 20 mM TPrA in 0.1 M PBS using the three-electrode system of carbon working electrode. As previously stated, these were the best conditions for the mobile phone-based ECL sensor development. Fig. 4 shows the generated images from the cell phone camera of the control assay (without the addition of dopamine). The use of the cell phone camera provided a visualized, quantitative detection approach for dopamine. The ECL intensity in the sensing zone (marked with a dotted circle) was quantified by processing the images from the camera using a mobile app/software. The RGB color intensity per pixel on the working electrode was a direct measure of the ECL intensity. There was a good linear correlation between the dopamine concentration and the ECL intensities as shown in Fig. 5A. The linear range is from 1.0 to 50 μM. The calibration equation is ECL = −0.2016 × dopamine +11.027 with a correlation coefficient of (R^2) of 0.982. When dopamine concentration was 50 μM, a complete quenching was observed. The ECL sensor has a wide range for dopamine detection with the limit of detection of 500 nM under the specified experimental conditions. It shows that the cell phone camera had a great potential for visualized detection.

Fig. 5B shows the Stern-Volmer (S—V) plot used to study the role of ECL quenching by dopamine and to determine the quenching rate constants. Usually, S—V plots exhibit linear behavior; however, an upward deviation is observed at high dopamine concentration. In this case, the quenching mechanism could be due to simultaneous dynamic and static quenching [23,24]. Parajuli et al. [22] point out that ECL quenching involves a dynamic quenching mechanism due to diffusive collisions between quencher and luminophore molecules during the lifetime of the excited state, avoiding ECL. The static quenching is related to the formation of a ground state quencher-luminophore complex, which does not produce ECL signal; however, the uncomplexed luminophores are able to emit ECL signals after excitation with normal excited state properties [24].

The linear S—V equation for dynamic quenching is given by Eq. (1).

$$\frac{I_0}{I} = (1 + K_{sv}Q) \tag{1}$$

where I_0 and I are the ECL intensities in the absence and presence of the quencher, respectively, K_{sv} ($=k_q\tau_0$) is the S—V dynamic quenching constant and Q is the quencher concentration. k_q is the biomolecular quenching constant, and τ_0 is the lifetime of luminophore in absence of the quencher.

The extended S—V equation (Eq. (2)) can be used to verify the ground state complex.

$$\frac{I_0}{I} = (1 + K_{sv}Q)(1 + k_aQ) \tag{2}$$

where k_a is the ground state association constant.

On the basis of ECL quenching experiments by dopamine in Fig. 5B (solid symbols), and the τ_0 for $Ru(bpy)_3^{2+}$ of 600 ns [25,26], the constants k_q ($=K_{sv}/\tau_0$) and k_a in Eq. (2) were adjusted. k_q was estimated to be $6.662 \times 10^{10}\ M^{-1}\ s^{-1}$ whereas k_a was $3.997 \times 10^4\ M^{-1}$. The estimation procedure of the constants used the generalized reduced gradient (GRG) algorithm embedded in Microsoft Excel.

Fig. 5B illustrates that Eq. (2) was particularly accurate to explain the upward deviation observed at a high dopamine concentration as determined by the $R^2 = 0.988$. In addition, the value of the constant k_q was equal to that obtained from adjustment of Eq. (1) at lower dopamine concentration region (linear portion) with $R^2 = 0.99$. According to Nagaraja et al. [27] and Koppal et al. [28], these results suggesting that

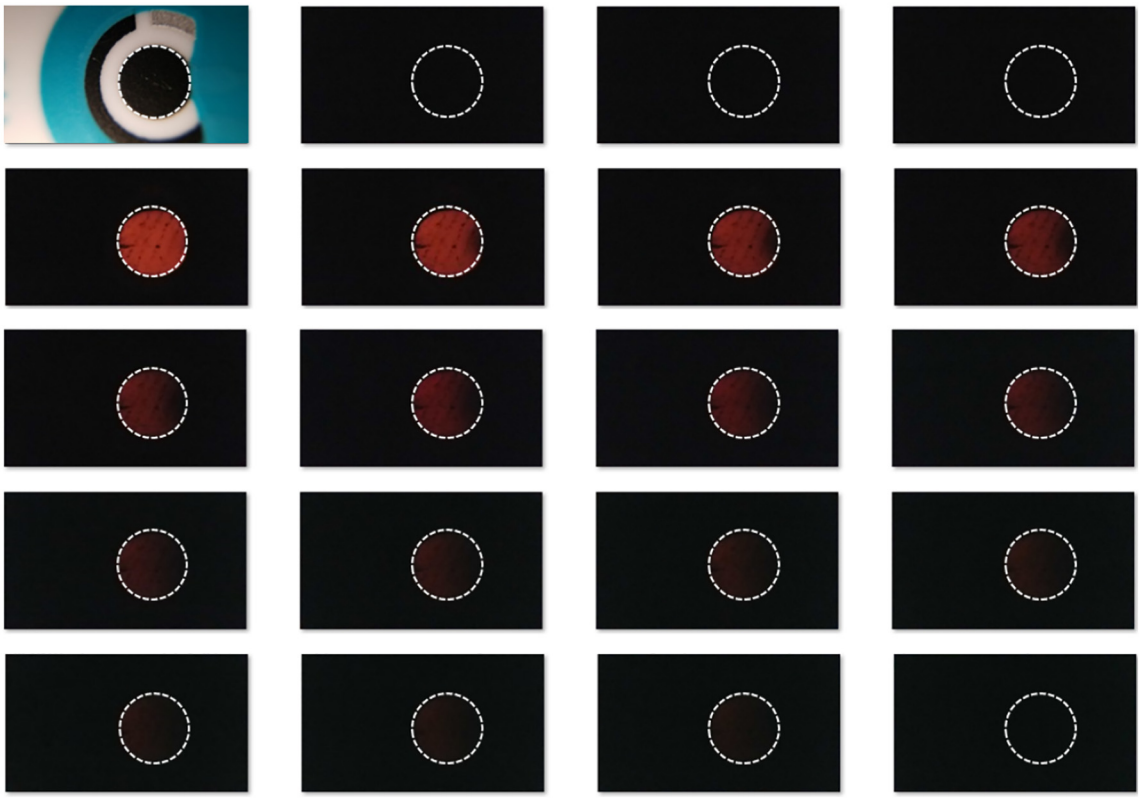

Fig. 4. Visualized quantitative ECL detection of control assay for detection of dopamine.

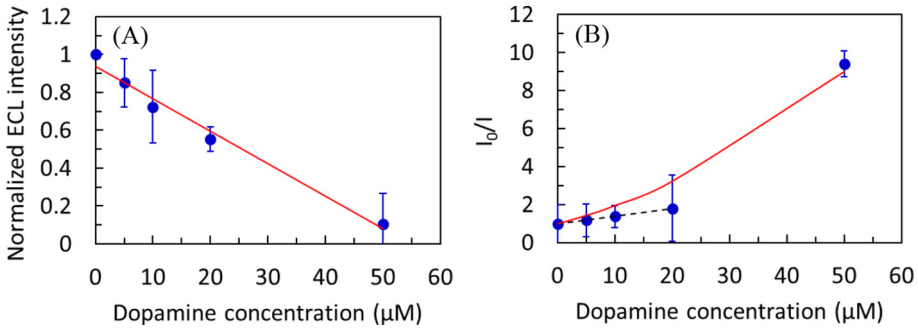

Fig. 5. A) Correlation between the dopamine concentration and the ECL intensities performed with 5 μM $Ru(bpy)_3^{2+}$ and 20 mM TPrA in 0.1 M PBS using three-electrode system of carbon SPE. The solid line is linear regression of the data; B) Stern-Volmer plot of ECL quenching by dopamine. The dashed and solid curves represent the plots of Eqs. (1) and (2) respectively.

along with the dynamic quenching mechanism, the ground state complex is formed in the system under study.

4. Conclusions

This study demonstrated how the developed mobile phone-based ECL sensor can be applied to detect the phenol-based compound of clinical significance: dopamine. This compound was used as an ECL quenching agent in the $Ru(bpy)_3^{2+}$/TPrA system. The most appropriate conditions to trigger the strongest ECL reaction, and visible to phone camera were: (i) The use of a three-electrode system with 12 mA current and low voltage (~1.2 V), (ii) a reaction system consisted of 5 μM $Ru(bpy)_3^{2+}$ and 20 mM TPrA in 0.1 M PBS. For the $Ru(bpy)_3^{2+}$/TPrA system, the developed sensor showed adequate repeatability and reproducibility in terms of RSD, which were below to 6.7%. The calculated values of quenching constants in the Stern-Volmer equations were an indication of simultaneous dynamic and static quenching mechanisms in the studied system. Further studies will expand the proposed approach to develop a practical and low-cost sensor for detection of other phenolic compounds of relevance in the field of bioeconomy.

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References

[1] S.E. Kirschbaum, A.J. Baeumner, A review of electrochemiluminescence (ECL) in and for microfluidic analytical devices, Anal. Bioanal. Chem. 407 (2015) 3911–3926.
[2] A.W. Knight, A review of recent trends in analytical applications of electrogenerated chemiluminescence, Trends in Analytical Chemsitry 18 (1999) 47–62.
[3] G. Hernandez-Vargas, J. Sosa-Hernández, S. Saldarriaga-Hernandez, A. Villalba-Rodríguez, R. Parra-Saldivar, H. Iqbal, Electrochemical biosensors: a solution to pollution detection with reference to environmental contaminants, Biosensors. 8 (2018) 29.
[4] Y. Zhang, R. Zhang, X. Yang, H. Qi, C. Zhang, Recent advances in electrogenerated chemiluminescence biosensing methods for pharmaceuticals, Journal of Pharmaceutical Analysis. 9 (1) (2018) 9–19.
[5] H. Wei, E.J.L. Wang, Electrochemiluminescence of tris (2, 2′-bipyridyl) ruthenium and its applications in bioanalysis: a review, Luminescence 26 (2) (2011) 77–85.
[6] H. Li, L.P. Zhou, J. Luo, J.P. Yu, H. Yang, H.P. Wei, Rapid colorimetric pyrazinamide susceptibility testing of *Mycobacterium tuberculosis*, The International Journal of Tuberculosis and Lung Disease. 20 (4) (2016) 462–467.
[7] M.A. Carvajal, J. Ballesta-Claver, A. Martinez-Olmos, L.F. Capitan-Vallvey, A.J. Palma, Portable system for photodiode-based electrochemiluminescence measurement with improved limit of detection, Sensors Actuators B Chem. 221 (2015) 956–961.
[8] M.-S. Kang, K.-P. Yoo, S.-I. Hong, N.-K. Min, Miniaturized ECL detection system for glucose biosensor. 3rd IEEE/EMBS special topic conference on microtechnology in medicine and biology, IEEE (2005) 229–232.
[9] J.L. Delaney, C.F. Hogan, Mobile phone based electrochemiluminescence detection in paper-based microfluidic sensors, Mobile Health Technologies. 1256 (2015) 277–289.
[10] J.L. Delaney, C.F. Hogan, J.F. Tian, W. Shen, Electrogenerated chemiluminescence detection in paper-based microfluidic sensors, Anal. Chem. 83 (2011) 1300–1306.
[11] Y. Yao, H. Li, D. Wang, C. Liu, C. Zhang, An electrochemiluminescence cloth-based biosensor with smartphone-based imaging for detection of lactate in saliva, Analyst. 142 (2017) 3715–3724.
[12] D. Meder, D.M. Herz, J.B. Rowe, S. Lehéricy, H.R. Siebner, The role of dopamine in the brain-lessons learned from Parkinson's disease, NeuroImage 190 (2018) 79–93.
[13] M.G. Tansey, M. Romero-Ramos, Immune system responses in Parkinson's disease: early and dynamic, Eur. J. Neurosci. 49 (2019) 364–383.
[14] N. Tukimin, J. Abdullah, Y. Sulaiman, Electrochemical detection of uric acid, Dopamine and Ascorbic Acid. Journal of the Electrochemical Society. 165 (2018) B258–B267.
[15] X. Liu, H. Jiang, J. Lei, H.J. Ju, Anodic electrochemiluminescence of CdTe quantum dots and its energy transfer for detection of catechol derivatives, Anal. Chem. 79 (2007) 8055–8060.
[16] A.J. Stewart, J. Hendry, L. Dennany, Whole blood electrochemiluminescent detection of dopamine, Anal. Chem. 87 (2015) 11847–11853.
[17] F. Gao, X.L. Cai, X. Wang, C. Gao, S.L. Liu, F. Gao, Highly sensitive and selective detection of dopamine in the presence of ascorbic acid at graphene oxide modified electrode, Sensor and Actuators B: Chemical. 186 (2013) 380–387.
[18] W. Miao, J.-P. Choi, A.J. Bard, Electrogenerated chemiluminescence 69: the Tris(2,2′-bipyridine)ruthenium(II), (Ru (bpy)$_3^{2+}$)/tri-*n*-propylamine (TPrA) system revisited a new route involving TPrA•$^+$ cation radicals, J. Am. Chem. Soc. 124 (2002) 14478–14485.
[19] Y. Zu, A.J. Bard, Electrogenerated chemiluminescence. 66. The role of direct coreactant oxidation in the ruthenium tris (2, 2′) bipyridyl/tripropylamine system and the effect of halide ions on the emission intensity, Anal. Chem. 72 (2000) 3223–3232.
[20] J. Lee, D.W. Arrigan, Silvester, Mechanical polishing as an improved surface treatment for platinum screen-printed electrodes, Sensing and Bio-Sensing Research. 9 (2016) 38–44.
[21] A. Martínez-Olmos, J. Ballesta-Claver, A. Palma, MdC Valencia-Mirón, L.J.S. Capitán-Vallvey, A portable luminometer with a disposable electrochemiluminescent biosensor for lactate determination, Sensors 9 (2009) 7694–7710.
[22] S. Parajuli, X. Jing, W.J. Miao, Electrogenerated chemiluminescence (ECL) quenching of the Ru (bpy)$_3^{2+}$/TPrA system by the explosive TNT, Electrochim. Acta 180 (2015) 196–201.
[23] A. Gong, X. Zhu, Y. Hu, S.J. Yu, A fluorescence spectroscopic study of the interaction between epristeride and bovin serum albumine and its analytical application, Talanta 73 (2007) 668–673.
[24] S.N. Patil, F. Sanningannavar, B. Navati, D. Nagaraja, N. Patil, R.J. Melavanki, Quenching mechanism of 5BDTC by aniline using Stern–Volmer plots, Can. J. Phys. 93 (2015) 1076–1081.
[25] G. Crosby, J.J. Demas, Quantum efficiencies on transition metal complexes. II. Charge-transfer luminescence, J. Am. Chem. Soc. 93 (1971) 2841–2847.
[26] B. Huang, X. Zhou, Z. Xue, G. Wu, J. Du, D. Luo, et al., Quenching of the electrochemiluminescence of Ru(bpy)$_3^{2+}$/TPA by malachite green and crystal violet, Talanta. 106 (2013) 174–180.
[27] D. Nagaraja, R. Melavanki, N. Patil, H. Geethanjali, R.J. Kusanur, Solvent effect on the relative quantum yield and fluorescence quenching of a newly synthesized coumarin derivative, Luminescencce 30 (2015) 495–502.
[28] V. Koppal, R. Melavanki, R. Kusanur, P. Bhavya, N.J. Patil, A role of solvent polarity on bimolecular quenching reactions of 3-acetyl-7-(diethylamino)-2H-chromen-2-one in binary solvent mixtures, J. Mol. Liq. 260 (2018) 221–228.