Biosensors and Bioelectronics 175 (2021) 112915

Contents lists available at ScienceDirect

Biosensors and Bioelectronics

journal homepage: http://www.elsevier.com/locate/bios

Short communication

Solid-phase microextraction integrated nanobiosensors for the serial detection of cytoplasmic dopamine in a single living cell

Yaran Chang [a,1], Yongjia Chen [b,1], Yunlong Shao [a], Boye Li [a], Yuanyuan Wu [a], Wenmei Zhang [a], Yingyan Zhou [a], Zhihui Yu [a], Liping Lu [a], Xiayan Wang [a,*], Guangsheng Guo [a,**]

[a] Center Excellence for Environmental Safety and Biological Effects, Beijing Key Laboratory for Green Catalysis and Separation, Department of Chemistry and Biology, Beijing University of Technology, Beijing, China

[b] Beijing Key Laboratory of Organic Materials Testing Technology and Quality Evaluation, Beijing Center for Physical and Chemical Analysis, Beijing, China

ARTICLE INFO

Keywords:
Dopamine
Cytoplasm
Solid-phase microextraction (SPME)
Electrochemistry
Nano-based biosensor

ABSTRACT

Dopamine participates in many physiological and pathological processes. Dynamic monitoring of dopamine levels in the cytoplasm of a single living cell reflects not only the functional state of dopamine synthesis factors but also the processes of related neurodegenerative diseases. Due to the low content of cytoplasmic dopamine and the difficulty to keep cells alive during the operating process, the detection of cytoplasmic dopamine is still challenging. Herein, a solid-phase microextraction (SPME) technique integrated nanobiosensor was employed to trace and quantify dopamine concentration fluctuations in the cytoplasm of a single living cell. We designed a polypyrrole modified carbon fiber nanoprobe as a bifunctional nanoprobe that can extract cytoplasmic dopamine and then perform electrochemical detection. This bifunctional nanoprobe can detect 10 pmol/L extracted dopamine and detected a 60% decrease of the cytoplasmic dopamine concentration in a single living cell by K^+ stimulation. This study allowed for the first time serially detecting cytoplasmic dopamine while keeping the target cell alive, which might yield a new method for research on dopamine neurotoxicity and the related drug action mechanisms for neurodegenerative disease.

1. Introduction

Dopamine, one of the most important monoamine neurotransmitters, is involved in a variety of physiological processes, including motor control, learning, and reward signaling (Mohebi et al., 2019; Sun et al., 2018). Altered dopamine levels are associated with multiple neurodegenerative diseases, such as Parkinson's disease (PD) (Burbulla et al., 2017) and schizophrenia (Grace, 2016). If dopamine in the cytoplasm is not immediately sequestrated into vesicles but accumulates in the cytoplasm, it will quickly form reactive oxygen species leading to enhanced oxidative stress and neurodegeneration (Lotharius and Brundin, 2002; Monzani et al., 2019). Dynamic changes in cytoplasmic dopamine content might reflect not only the functional characteristics of dopamine biosynthesis but also metabolism factors, which could provide more prehensive information about the physiological and pathological processes, such as neurodegenerative diseases.

An as-yet unrealized goal is to develop a method to reliably and specifically measure dopamine changes with high spatiotemporal precision (Sun et al., 2018). Significant advances have been achieved in the detection of dopamine vesicles. In the 1990s, Wightman et al. used carbon fiber electrodes for the first time for the real-time detection of catecholamine exocytosis out of a single bovine adrenal medullary chromaffin cell (Wightman et al., 1991). Huang et al. monitored the release of dopamine from a single pheochromocytoma (PC12) cell (Li et al., 2014; Wu et al., 2005). Ewing et al. successfully detected the neurotransmitters of vesicles in the cell cytoplasm environment (Li et al., 2015), also measured the content of catecholamines in the vesicles (Zhang et al., 2020). These methods provide much information about dopamine in vesicles. However, the concentration of cytosolic dopamine is much lower than that in vesicles, and measuring it requires analytical methods with high sensitivity to dopamine and limits the effect on cell viability. Because of these complications, few studies have been conducted to detect the concentration of cytosolic dopamine in a single cell. Mosharov et al. used "intracellular patch electrochemistry" to break into

* Corresponding author.
** Corresponding author.
E-mail addresses: xiayanwang@bjut.edu.cn (X. Wang), gsguo@bjut.edu.cn (G. Guo).
[1] Yaran Chang and Yongjia Chen contributed equally.

https://doi.org/10.1016/j.bios.2020.112915
Received 6 September 2020; Received in revised form 15 December 2020; Accepted 17 December 2020
Available online 28 December 2020

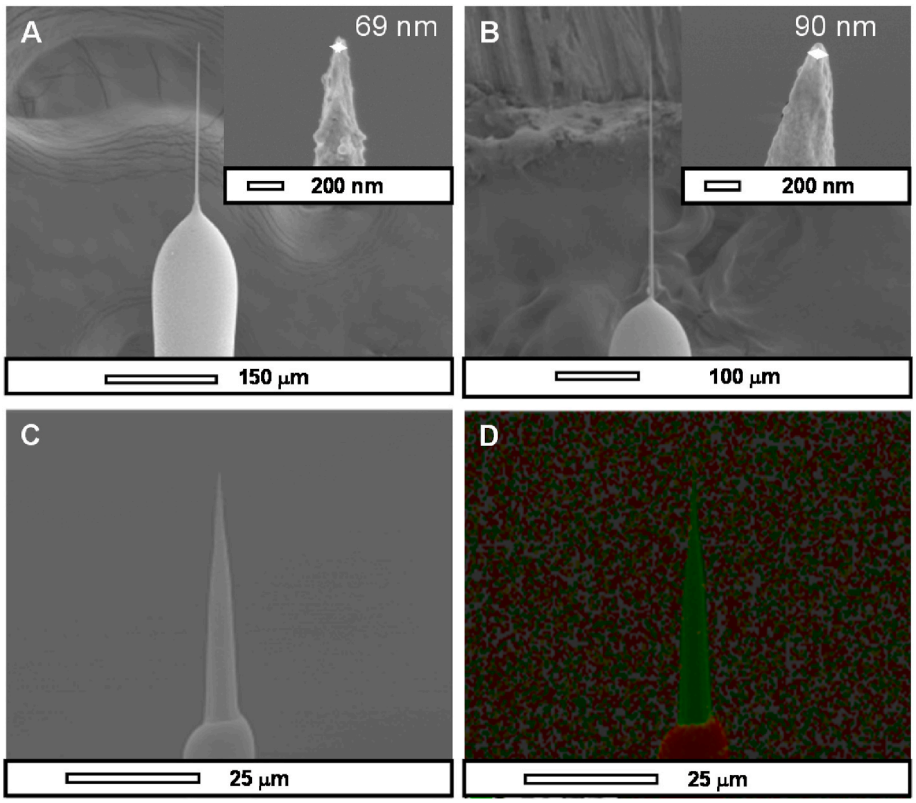

Fig. 1. Characterization of the bifunctional nanoprobe and its glass/carbon fiber interface. **(A)** SEM image of the bare carbon fiber nanoprobe (the inset shows the conical nanotip of the carbon fiber nanoprobe). **(B)** SEM image of the PPy-coated carbon fiber nanoprobe (the inset shows the tip of the PPy-coated carbon fiber nanoprobe). **(C)** SEM image of the flame sealed glass/carbon fiber interface. **(D)** EDX element mapping image with an overlay of Si and C signals.

a cell to directly measure cytosolic catecholamine levels (Mosharov et al., 2003). This method destroys the cells and cannot obtain continuous information about the cells. The continuous detection of the amount of intracellular dopamine relative to extracellular dopamine and a single time detection can provide abundant and accurate information about the physiological conditions of the cell.

The electrochemical methods have often been applied to biological sample analysis due to their high sensitivity (Atci et al., 2016; Oomen et al., 2019). For several decades, carbon fiber microelectrodes have often been used for electrical measurements of single-cell analysis because of their good biocompatibility (Hou et al., 2020). Dopamine, a redox-active neurotransmitter, is preferred to detect by electrochemical methods (Sajid et al., 2019; Sun et al., 2020). Solid-phase microextraction (SPME) is a sample pretreatment method that combines sampling, analyte extraction, and enrichment in a single step (Vuckovic et al., 2011). Compared with traditional extraction techniques, SPME has the advantages of rapid preconcentration, non-exhaustive extraction, and no disruption of system balance (Reyes-Garces et al., 2018). In recent years, SPME has been applied in the field of biological sample analysis (Napylov et al., 2019). Flame-etched carbon fiber nanoprobes, which are typically conical tips employed as SPME substrate probes that can also be used for electrochemical nanobiosensors to serially detect the cell cytoplasm dopamine content. In this work, polypyrrole (PPy) is used to modify the carbon fiber nanoprobe as the SPME extraction coating and electrode-modified material due to the excellent conductivity, environmental safety, nontoxicity, and biocompatibility of PPy (Zhao et al., 2019). Then a bifunctional nanoprobe that combines the SPME fiber and a working electrode (WE) for electrochemical detection in one system is obtained. Here, we report a bifunctional nanoprobe used in the detection of 10 pmol/L extracted dopamine; also, the serial detection of the cytoplasmic dopamine content in the same living cell, 60% of cytoplasmic dopamine concentration of this cell is released after K^+ stimulation. Serial detection of cytoplasmic dopamine in the same cell may provide a new way to research physiological mechanisms, such as dopamine synthesis and transmission, disease occurrence, and drug-cell interactions.

2. Materials and methods

2.1. Chemicals and solutions

Dopamine hydrochloride, serotonin hydrochloride, uric acid, ascorbic acid, and pyrrole were purchased from Sigma-Aldrich (St. Louis, MO). Carbon fiber was obtained from Toray Industries, Inc. (Japan). RMPI-1640 phenol red-free culture medium, heating-inactivation horse serum, fetal bovine serum and penicillin-streptomycin were bought from Gibco (USA). $Na_2HPO_4{\cdot}12H_2O$, KH_2PO_4, NaOH, KCl, acetone, hydrochloric acid, nitric acid, and sulfuric acid were from Beijing Chemical Works (Beijing, China). Hydrofluoric acid (40% v/v) was made by Tianjin Fuchen Chemical Reagent Factory (Tianjin, China). Ethanol was produced by Sinopharm Chemical Reagent Co., Ltd. Methanol (HPLC grade) was obtained from Thermo Fisher Scientific (USA). All reagents used were Analytical Reagent or better. All solutions were prepared with 18.2 MΩ cm water from a GenPure ultrapure water system (Thermo Scientific). 0.1 mol/L phosphate-buffered saline (PBS) was made by 0.1 mol/L Na_2HPO_4, and 0.1 mol/L KH_2PO_4 mixed at a volume ratio of about 81:19, and 0.1 mol/L KCl was added, then modify the pH to 7.4 by a pH meter (PB-10, Sartorius, Germany). Dopamine, serotonin (5-HT), ascorbic acid (AA), and uric acid (UA) solutions were prepared in fresh-prepared PBS buffer, respectively. These solutions were degassed with argon (Ar) to remove oxygen.

2.2. Electrochemical experiments

All electrochemical experiments were performed by a CHI 852D electrochemical workstation (CH Instruments, Shanghai, China). A three-electrode system was employed. A carbon fiber nanoprobe or a bifunctional nanoprobe was acting as a WE. An Ag/AgCl (saturated KCl) electrode or an Ag wire coated with AgCl serving was used as the reference electrode (RE), and a platinum (Pt) wire was used as the counter electrode (CE). The pulse period and amplitude of DPV measurements are 0.5 s and 50 mV, respectively.

2.3. Fabrication of carbon fiber nanoprobes

Carbon fibers with 7 μm diameter (TORAY, Japan) were firstly cleaned by sonication in deionized water for 5 min, 30% HNO_3 for 20 min, acetone for 10 min, ethanol for 10 min and deionized water for 5 min, in sequence. Then it was dried by infrared light and standby. The glass capillaries of 0.9 mm I.D., 1.8 mm O.D. and 100 mm length (Yixing sliver star analyzing & experiment apparatus factory, China) were pulled into two separate pipettes with a tip of ~20 μm using a PC-100 pipette puller (Narishige Co., Ltd., Japan). A carbon fiber was inserted into the above-mentioned pipette; the end of the carbon fiber is 5 mm away outside of the pipette tip. The protruded carbon fiber was sealed in the pipette and etched carefully to a conical tip of less than 100 nm by flame. The length of exposure of carbon fiber was ~200 μm. Then, a copper wire was contacted with carbon fiber through silver paste conductive adhesive (Sino-platinum Metals CO., Ltd, China) from the end of the capillary, then, using infrared light to dry the adhesive. Next, epoxy glue was used to seal the end of the capillary to fix the copper wire. The prepared carbon fiber probe was placed upright with the tip of carbon fiber upward. Characterization of the glass/carbon fiber interface by the energy-dispersive X-ray (EDX) (SU8020, Hitachi, Japan).

2.4. Preparation of bifunctional nanoprobes

The above-prepared carbon fiber nanoprobe was activated by scanning for 25 circles from 0.2 V to 1.2 V in 0.5 mol/L H_2SO_4, until the curves of cyclic voltammetry (CV) were stable. Then the carbon fiber nanoprobe was rinsed by deionized water and dried by infrared light. Next, the carbon fiber nanoprobe was submerged in the electrolyte solution, which contained 0.015 mol/L pyrrole and 0.1 mol/L hydrochloride. Before used, pyrrole is purified by a rotary evaporator (RE-201D, Beijing Shentai Weiye Instrument Equipment Co., Ltd., China). A constant potential of 1.2 V for 10 s was applied for the carbon fiber nanoprobe. Then, a homogeneous PPy coating of ~10 nm was formed onto the surface of the carbon fiber nanoprobe tip. The PPy modified carbon fiber nanoprobe was rinsed by deionized water, dried by infrared light, and activated by scanning from 0 V to 1 V in 1.0 mol/L NaOH solution for about 25 circles until the curves of CV were stable. Then, it was rinsed by deionized water, dried by infrared light and ready for use. After all steps were finished, the PPy modified bifunctional nanoprobe was obtained. The surface morphology of the nanoprobes was observed by scanning electron microscopy (SEM) (S4800, Hitachi, Japan).

3. Results and discussion

3.1. Fabrication and characterization of the bifunctional nanoprobe

Here we describe the serial detection of cytoplasmic dopamine level in single living cells using a bifunctional nanoprobe. A carbon fiber acts as the substrate of the bifunctional nanoprobe, which is placed inside a glass capillary and then sealed by flame. Additionally, the cylindrical carbon fiber is carefully flame etched to fabricate a conical nanotip (diameter at top: 69 nm, the inset of Fig. 1A). The SEM image of cylindrical carbon fiber is shown in Fig. S1. It is well known that poor sealing characteristics and electrode leakage cause high noise, electrode pollution and even a shortened electrode life. Based on the EDX map for the elements C and Si, Si is relatively abundant in the sealing area, as a major component of glass, and C in the nanotip is distributed uniformly (Fig. 1C and D). The EDX map of Si and C indicates that the glass/carbon fiber interface is well sealed and has no effect on the exposure of the carbon fiber tip.

A uniform and stable PPy coating is obtained through pyrrole polymerization on the etched carbon fiber nanoprobe surface by controllable electrodeposition (Fig. S2 and Fig. S3). Although the increased thickness of the PPy coating over a certain range improved the extraction effect of dopamine concentrations, the tip diameter of the bifunctional probe became large, which severely reduced cell viability. According to the reported work, the probes do not significantly affect cell viability when they have a tip with a diameter of less than 100 nm that is directly inserted into a cell (Simonis et al., 2017; Ying et al., 2018). Considering the above factors, the thickness of the PPy coating electrodeposited on the carbon fiber tip was approximately 10 nm, as determined from the difference in the diameters of the uncoated and coated probes, and the diameter of the modified bifunctional nanoprobe was still less than 100 nm (the inset of Fig. 1B). The bifunctional nanoprobe, acting as the WE, was evaluated for electrochemical performance in a three-electrode system by CV measurements. Well-defined sigmoidal voltammograms in 10 mmol/L $K_3[Fe(CN)_6]/K_4[Fe(CN)_6]$ were observed (Fig. S4). Due to the enrichment effect of the bifunctional nanoprobe on samples, the nanoprobe has a high sensitivity to dopamine and can be used to detect 10 pmol/L dopamine in the sample after extraction (Figs. S5 and S6).

3.2. Sensitivity and specificity of the bifunctional nanoprobe to dopamine

Electro-active compounds such as epinephrine (EP), UA, 5-HT, and AA often coexist in biological samples. Moreover, it is challenging to detect dopamine in the presence of these electro-active compounds because of their similar oxidation potentials, which result in overlapping signals (Xu et al., 2018). In reported work, no EP was detected in PC12 cells (Greene and Tlschler, 1976), and there is, therefore, no need to consider interference from EP during the electrochemical detection of dopamine when PC12 cells are used. The dopamine oxidation peak potential measured in PBS (pH = 7.4) by differential pulse voltammetry (DPV) is approximately 0.15 V (vs. Ag/AgCl), while the oxidation peak potentials of AA, 5-HT and UA are approximately 0.00 V, 0.34 V, and 0.36 V, respectively (Fig. S7). Due to proton participation in the electrochemical reaction, the different pH of solutions may lead to oxidation peak potential have a slight shift; also, different electrode materials and electrode modification materials may result in a slightly different oxidation peak potential; moreover, the oxidation peak potential in this work matches the previous work generally (Liu et al., 2018; Yang et al., 2019). Although the peak potentials of UA and 5-HT are very similar to obtain the overlapping signals, it does not affect the detection of the target analyte dopamine. Dopamine exists with a positive charge in body fluid and brain tissues, while AA and UA are often negatively charged (Diab et al., 2019). The PPy coating plays the role of a cation-permeable membrane, which benefits from its negatively charged surface, particularly it is activated in NaOH solution at 1 V resulting in overoxidation (Sajid et al., 2019; Sasso et al., 2013). Thus, it has a strong attraction effect and high sensitivity to dopamine while almost no extraction even rejective effect and poor sensitivity to AA and UA (Figs. S7B, S7D, and S8). Therefore, the bifunctional nanoprobe is not subject to interference by other electro-active compounds for dopamine detection in real biological samples.

During the single living cell cytoplasm dopamine extraction experiment, as the extraction time increased, the physiological state of the cell gradually deteriorated, even resulting in cell death. To reduce cell damage and ensure extraction, the dopamine extraction time with the bifunctional nanoprobe was optimized. When the extraction time was more than 180 s, the distribution of dopamine in the extraction phase and in the sample solution basically reached equilibrium (Fig. S9).

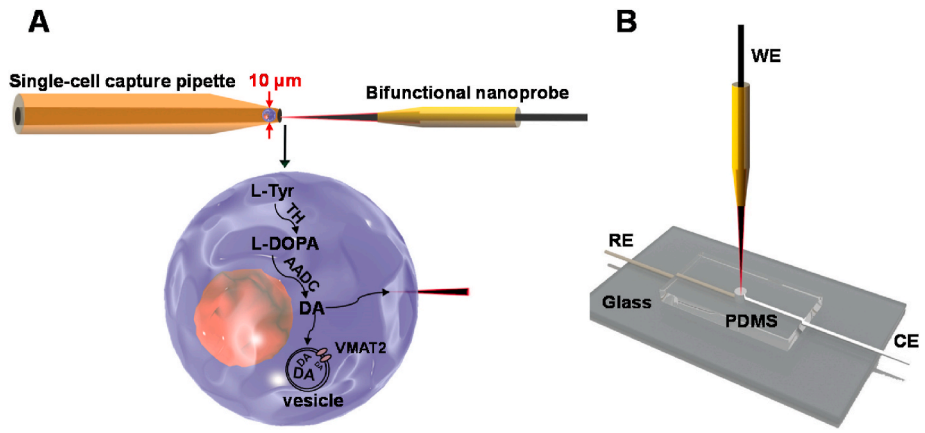

Fig. 2. Schematic representation of detecting cytoplasmic dopamine in a single living cell. **(A)** The schematic of SPME of a living cell in a single-cell capture pipette by a bifunctional nanoprobe. **(B)** The schematic of electrochemical detection using an after extracted bifunctional nanoprobe as a WE.

Therefore, in subsequent experiments, 180 s was chosen as the extraction time. To verify the quantitative capability of this method, the bifunctional nanoprobe was immersed into dopamine solutions with different concentrations extracted for 180 s, and then DPV measurements were performed (Fig. S10). As the dopamine concentration in the sample increases, the average peak current increases linearly, and excellent linearity ($R^2 = 0.9862$) is achieved in the concentration range of 20 nmol/L to 300 nmol/L, which proves that the average dopamine sensitivity has a linear correlation and that the probe is well-suited to dopamine quantitative analysis.

3.3. Fabrication of single-cell capture pipette and SPME of single cell

The experimental results showed that the bifunctional nanoprobe could extract and detect dopamine in real biological samples. In Fig. S11, we use this bifunctional nanoprobe for single-cell SPME in 10 single PC12 cells, the concentrations of intracellular dopamine here observed is 4–559 nmol/L, and most of this is less than 100 nmol/L (8 of 10 cells). To facilitate the observation and manipulation of a single cell, a single-cell capture pipette is needed. Wang et al. provide a robust method to etch the capillary outside surface with hydrofluoric acid and a rapidly flowing protective fluid is used to protect the capillary inner surface from etching (Shao et al., 2020). Based on this method, a capillary with an identical inner diameter (10 μm) and a thinner outer wall at the tip (15–20 μm) was fabricated (Fig. S12). The unetched side of the capillary was then connected with a syringe to be served as a single-cell capture pipette which was used to unharmed selectively capture a single PC12 cell from the cell suspension. A single PC12 cell was fixed at the opening of this capture pipette tip; then, the bifunctional nanoprobe was inserted into the living PC12 cell to carry out SPME of dopamine (Fig. 2A and Fig. S13). Because only a small amount of culture medium exists in the port of the capture pipette, unexpected severe desorption of the extracted dopamine is avoided when the nanoprobe is removed from the pipette at the end of the extraction process.

3.4. Serial detection of a single living cell cytoplasmic dopamine

Stimulation of K^+ depolarizes the cells and causes cytosolic dopamine release by exocytosis (Abe et al., 2015). To study the influence of K^+ on the release of dopamine in single living cells, the intracellular dopamine content in a single living PC12 cell was measured before and after K^+ stimulation. The low quantity of dopamine in a single-cell sample is enriched by the bifunctional nanoprobe in a single-cell capture pipette; electrochemical detection is directly carried out without performing an extra desorption process, which avoids the severe dilution of the analyte (Fig. 2). The bifunctional nanoprobe will be activated before the next time the electrode is used. Then this cell was stimulated by 80 mmol/L KCl for 180 s. Subsequently, a second extraction and detection cycle of this living cell was performed. For DPV measurements, the oxidation peak current after stimulation was approximately 40% of that before stimulation, so the stimulation of KCl led to the release of approximately 60% of dopamine from the cytoplasm (Fig. 3). As shown in Fig. 3A, a slight oxidation peak of AA can be observed at 0.00 V; it makes no interference for dopamine detection. To get a clearer view of the fluctuation in cytoplasmic dopamine, we have subtracted the background and AA peak in Fig. 3B. In order to demonstrate the

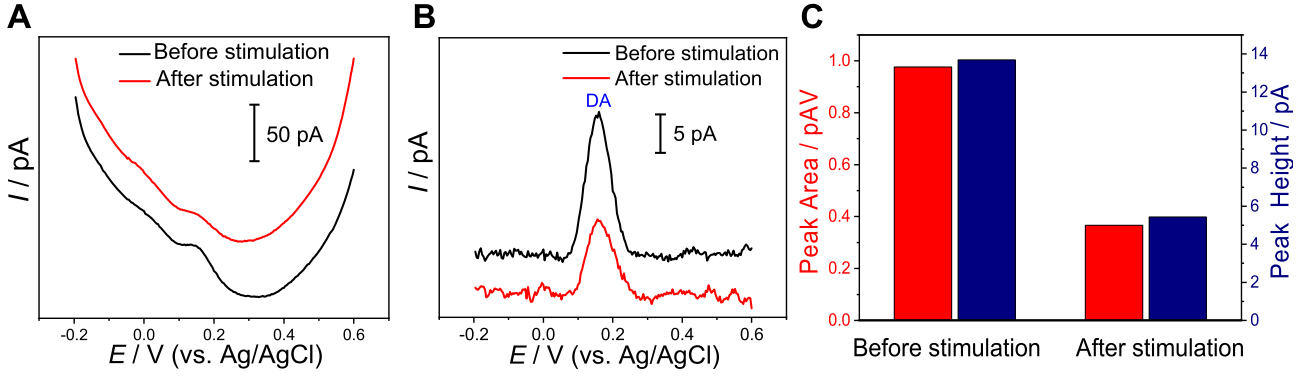

Fig. 3. Electrochemical detection of cytosolic dopamine in a single living PC12 cell before and after K^+ stimulation. **(A)** DPV measurements of dopamine (DA) and ascorbic acid extracted from the cytoplasm. **(B)** Background-subtracted and ascorbic acid peak-subtracted curves of **(A)**. **(C)** Oxidation peak area and height of DPV measurements. The pulse period and amplitude of DPV measurements are 0.5 s and 50 mV, respectively.

depolarization effect of K^+ on cells, the blank experiment was performed with no stimulation. Without KCl stimulation, the cell release approximately 21% of dopamine from the cytoplasm during the two times extraction (Fig. S14). After a set of operations was completed, the cell was returned to the culture medium, and trypan blue was applied to dye this cell. From the photomicrograph of the cell used in this experiment, trypan blue did not stain the cell blue, indicating that the cell was still alive (Fig. S15). The results show that the bifunctional nanoprobe has a minimal effect on cell function and can be employed for the real-time continuous detection of dopamine in the cytoplasm of a single living cell.

4. Conclusion

In summary, we have developed an SPME-electrochemical detection system capable of serially detecting dopamine in the cytoplasm of a single living cell by using a novel and versatile bifunctional nanoprobe. A bifunctional nanoprobe with a tiny nanotip ($\leq$100 nm) showed excellent properties to the detection of 10 pmol/L dopamine in samples after extraction. When inserted into the same cell two times for extraction before and after K^+ stimulation, the nanoprobe detected a 60% decrease of the cytoplasmic dopamine concentration. The serial detection of cytoplasmic dopamine in a single cell is a new biochemical method that can find out cells with abnormal metabolism of dopamine and discern the physiological state of the cell, moreover it could provide a novel method for dopamine neurotoxicity and related drug action mechanisms for the neurodegenerative disease.

CRediT authorship contribution statement

Yaran Chang: Methodology, Formal analysis, Writing - original draft. **Yongjia Chen:** Methodology, Formal analysis, Investigation. **Yunlong Shao:** Methodology, Formal analysis. **Boye Li:** Formal analysis, Investigation. **Yuanyuan Wu:** Methodology. **Wenmei Zhang:** Investigation. **Yingyan Zhou:** Writing - review & editing. **Zhihui Yu:** Writing - review & editing. **Liping Lu:** Writing - review & editing. **Xiayan Wang:** Conceptualization, Methodology, Funding acquisition, Project administration, Writing - review & editing, Supervision. **Guangsheng Guo:** Methodology, Formal analysis, Funding acquisition, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (Nos. 21625501, 21527808, 21936001), the Beijing Outstanding Young Scientist Program (BJJWZYJH01201910005017), the Beijing Municipal High Level Innovative Team Building Program (IDHT20180504), and the Young Elite Scientist Sponsorship Program of Beijing Association for Science and Technology.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bios.2020.112915.

References

Abe, H., Ino, K., Li, C.Z., Kanno, Y., Inoue, K.Y., Suda, A., Kunikata, R., Matsudaira, M., Takahashi, Y., Shiku, H., Matsue, T., 2015. Anal. Chem. 87, 6364–6370.
Atci, E., Babauta, J.T., Sultana, S.T., Beyenal, H., 2016. Biosens. Bioelectron. 81, 517–523.
Burbulla, L.F., Song, P., Mazzulli, J.R., Zampese, E., Wong, Y.C., Jeon, S., Santos, D.P., Blanz, J., Obermaier, C.D., Strojny, C., Savas, J.N., Kiskinis, E., Zhuang, X., Krüger, R., Surmeier, D.J., Krainc, D., 2017. Science 357, 1255–1261.
Diab, N., Morales, D.M., Andronescu, C., Masoud, M., Schuhmann, W., 2019. Sensor. Actuator. B Chem. 285, 17–23.
Grace, A.A., 2016. Nat. Rev. Neurosci. 17, 524–532.
Greene, L.A., Tlschler, A.S., 1976. Proc. Natl. Acad. Sci. U.S.A. 73, 2424–2428.
Hou, H., Jin, Y., Wei, H., Ji, W., Xue, Y., Hu, J., Zhang, M., Jiang, Y., Mao, L., 2020. Angew. Chem. Int. Ed. 59, 18996–19000.
Li, X., Majdi, S., Dunevall, J., Fathali, H., Ewing, A.G., 2015. Angew. Chem. Int. Ed. 54, 11978–11982.
Li, Y.T., Zhang, S.H., Wang, L., Xiao, R.R., Liu, W., Zhang, X.W., Zhou, Z., Amatore, C., Huang, W.H., 2014. Angew. Chem. Int. Ed. 53, 12456–12460.
Liu, Z., Jin, M., Cao, J., Niu, R., Li, P., Zhou, G., Yu, Y., van den Berg, A., Shui, L., 2018. Sensor. Actuator. B Chem. 273, 873–883.
Lotharius, J., Brundin, P., 2002. Nat. Rev. Neurosci. 3, 932–942.
Mohebi, A., Pettibone, J.R., Hamid, A.A., Wong, J.T., Vinson, L.T., Patriarchi, T., Tian, L., Kennedy, R.T., Berke, J.D., 2019. Nature 570, 65–70.
Monzani, E., Nicolis, S., Dell'Acqua, S., Capucciati, A., Bacchella, C., Zucca, F.A., Mosharov, E.V., Sulzer, D., Zecca, L., Casella, L., 2019. Angew. Chem. Int. Ed. 58, 6512–6527.
Mosharov, E.V., Gong, L.-W., Khanna, B., Sulzer, D., Lindau, M., 2003. J. Neurosci. 23, 5835–5845.
Napylov, A., Reyes-Garces, N., Gomez-Rios, G., Olkowicz, M., Lendor, S., Monnin, C., Bojko, B., Hamani, C., Pawliszyn, J., Vuckovic, D., 2019. Angew. Chem. Int. Ed. 58, 2392–2398.
Oomen, P.E., Aref, M.A., Kaya, I., Phan, N.T.N., Ewing, A.G., 2019. Anal. Chem. 91, 588–621.
Reyes-Garces, N., Gionfriddo, E., Gomez-Rios, G.A., Alam, M.N., Boyaci, E., Bojko, B., Singh, V., Grandy, J., Pawliszyn, J., 2018. Anal. Chem. 90, 302–360.
Sajid, M., Baig, N., Alhooshani, K., 2019. TrAC Trends Anal. Chem. 118, 368–385.
Sasso, L., Heiskanen, A., Diazzi, F., Dimaki, M., CastilloLéon, J., Vergani, M., Landini, E., Raiteri, R., Ferrari, G., Carminati, M., Sampietro, M., Svendsena, W.E., 2013. Analyst 138, 3651–3659.
Shao, Y., Zhou, Y., Wu, Y., Zhang, Q., Yu, Z., Guo, G., Wang, X., 2020. Talanta 218, 121096.
Simonis, M., Hubner, W., Wilking, A., Huser, T., Hennig, S., 2017. Sci. Rep. 7, 41277.
Sun, F., Zeng, J., Jing, M., Zhou, J., Feng, J., Owen, S.F., Luo, Y., Li, F., Wang, H., Yamaguchi, T., Yong, Z., Gao, Y., Peng, W., Wang, L., Zhang, S., Du, J., Lin, D., Xu, M., Kreitzer, A.C., Cui, G., Li, Y., 2018. Cell 174, 481–496.
Sun, X., Zhang, L., Zhang, X., Liu, X., Jian, J., Kong, D., Zeng, D., Yuan, H., Feng, S., 2020. Biosens. Bioelectron. 153, 112045.
Vuckovic, D., Risticevic, S., Pawliszyn, J., 2011. Angew. Chem. Int. Ed. 50, 5618–5628.
Wightman, R.M., Jankowskl, J.A., Kennedy, R.T., Kawagoe, K.T., Schroeder, T.J., Leszczyszyn, D.J., Near, J.A., Diliberto, E.J., Viveros, O.H., 1991. Proc. Natl. Acad. Sci. U.S.A. 88, 10754–10758.
Wu, W.-Z., Huang, W.-H., Wang, W., Wang, Z.-L., Cheng, J.-K., Xu, T., Zhang, R.-Y., Che, Y., Liu, J., 2005. J. Am. Chem. Soc. 127, 8914–8915.
Xu, G., Jarjes, Z.A., Wang, H.W., Phillips, A.R.J., Kilmartin, P.A., Travas-Sejdic, J., 2018. ACS Appl. Mater. Interfaces 10, 42136–42145.
Yang, H., Zhao, J., Qiu, M., Sun, P., Han, D., Niu, L., Cui, G., 2019. Biosens. Bioelectron. 124–125, 191–198.
Ying, Y.L., Li, Y.J., Mei, J., Gao, R., Hu, Y.X., Long, Y.T., Tian, H., 2018. Nat. Commun. 9, 3657.
Zhang, X.W., Hatamie, A., Ewing, A.G., 2020. J. Am. Chem. Soc. 142, 4093–4097.
Zhao, N., Ma, Z., Song, H., Xie, Y., Zhang, M., 2019. Electrochim. Acta 296, 69–74.