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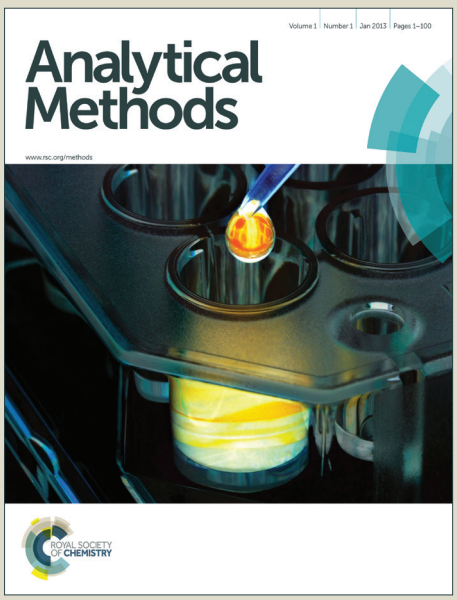

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Electrochemical Deoxyribonucleic Acid Biosensor for Rapid Genotoxicity Screening of Chemicals

Lidong Wu[‡2], Xianbo Lu[*‡1], Xue Wang[1], Yi Song[2], Jiping Chen[*1]

1. Key Laboratory of Separation Science for Analytical Chemistry, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, China
2. Chinese Academy of Fishery Sciences, Beijing 100141, China

Abstract:

A sensitive electrochemical biosensor based on double-stranded deoxyribonucleic acid (DNA) has been proposed for rapid screening of chemicals genotoxicity potential. DNA probe from clone RP3-402G11 gene of human DNA sequence and electroactive methylene blue (MB) have been used as biorecognition element and signal amplification molecules respectively for evaluating the genotoxic potential of target analytes with high sensitivity. The biosensing mechanism of genotoxicity screening is based on the damage of targets for the DNA double helix, which results in the subsequent distinct change of electrochemical signal. More than 10 kinds of genotoxic chemicals have been used as testing analytes including highly toxic dioxins (polychlorinated dibenzodioxins, polychlorinated dibenzofurans) and polychlorinated biphenyls (PCBs). Dioxins and dioxin-like chemicals have been identified as highly

‡the authors contribute equally to this work.

*Corresponding author. Tel/Fax: 86-411-84379562; E-mail: xianbolu@dicp.ac.cn, chenjp@dicp.ac.cn.

‡the authors contribute equally to this work.

genotoxic chemicals by the proposed DNA biosensor, which is consistent with the conclusion from International Agency for Research on Cancer. The results obtained demonstrated that the signal response of the biosensor for dioxins and PCBs was correlative to their toxic equivalent factor (TEF) values and their concentration of tested targets. The biosensor proved to be a promising in vitro screening tool for rapid estimation of chemicals genotoxicity potential.

Keywords: Toxicity screening; Dioxin-like chemicals; Benzene derivative; Chemicals genotoxicity potential; Electrochemical deoxyribonucleic acid biosensor

1. Introduction

Environmental security is one of the most fundamental concerns in the global society nowadays[1]. Due to the economic development including industry, agriculture etc., use of chemicals has increased dramatically. Of the estimated 100 000 chemicals which exist within the global market, 10 000 chemicals are hazardous, out of which about 200-300 are confirmed carcinogenic agents[2]. In addition to this, thousands of new chemicals are being produced and utilized each year, many of which, results in a number of adverse health effects including cancer and organ damage[3]. How to rapidly screen and predict chemicals toxicity potential is essential. Recently, Mahadevan et al. described that the field of genetic toxicology testing in the 21st century faces two challenges[4]. “The first challenge is to take full advantage of new technologies to improve our ability to access the impacts of chemically induced genetic damage. Second is the use of these technologies for reliable assessment of new and existing

chemicals for genetic toxicity potential more efficiently, cost effectively and with less reliance on animal models". Currently, genotoxicity testing techniques are mainly being performed in bacterial, yeast[5], tissue[6] and mammalian cells[7]. But these recommended tests are very laborious, time-consuming and require complicated experimental procedures with highly trained technicians. In order to avoid unnecessary in vivo testing, there is a crucial need to develop alternative in vitro testing method which could be used to estimate risks of adverse effects from chemical exposures and use those estimations to help people from potential harm.

Electrochemical oligonucleotide (E-DNA) biosensor has been developed for screening of some toxic chemicals based on DNA damage[8-10]. Ozsoz et al. developed an E-DNA biosensor for monitoring arsenic trioxide through the changes of guanine oxidation signals[11, 12]. However, most of the previous studies, were focused on developing biosensor for the detection of certain kind of contaminants[13-15] and few studies have evaluated the feasibility of E-DNA biosensor for the genotoxicity screening of chemicals. Hart et al. developed a biosensor for detecting potassium dichromate as genotoxic chemical by monitoring the changes in adenine, guanine and 8-oxyguanine[16]. Rusling et al. fabricated an inexpensive and rapid biosensor for genotoxicity screening (arylamine metabolism) that detected *N*-acetyltransferase enzyme-induced DNA damage[17]. Literature survey reveals very few reports on the genotoxicity screening by E-DNA biosensor and most of them used a specific genotoxic chemical as an analyte. Thus developing an E-DNA biosensor for feasibility study on genotoxicity screening is of great importance.

Herein we presented a novel E-DNA biosensor based on dsDNA probe (from clone RP3-402G11 gene of human DNA sequence) and electroactive methylene blue for rapid screening and evaluation of chemicals genotoxicity potential with high sensitivity. The dsDNA probe from clone RP3-402G11 gene of human DNA sequence was used as the bio-recognition element for the fabrication of an E-DNA biosensor. The sensitivity of the biosensor can be improved significantly, using electroactive molecule methylene blue as an indicator for signal amplification[18-20]. The developed E-DNA biosensor has been used for systematic screening & estimation of genotoxicity potential activity of dioxins (PCDDs, PCDFs), PCBs, dioxin-like chemical (e.g. 2, 3, 7, 8-Tetrabromodibenzofuran) and benzene derivative. Polychlorinated dibenzodioxins (PCDDs)[21, 22], polychlorinated dibenzofurans (PCDFs)[23, 24], polychlorinated biphenyls (PCBs)[25, 26] and many benzene derivatives are potential genotoxic pollutants which are widely disseminated in the environment. These hypertoxic chemicals can cause serious environmental problems due to their mutagenic effects and bioaccumulation in ecosystem[27]. The obtained results demonstrated that the fabricated E-DNA biosensor was a promising tool for estimating the chemicals genotoxicity potential. The developed E-DNA biosensor can be an interesting alternative to assess new and existing chemicals for genetic toxicity potential, more efficiently, cost effectively with less reliance on animal models.

2. Experimental Section

2.1 Materials and Solutions.

6-mercapto-1-hexanol (MCH) was provided by J&K chemical Ltd. (Sweden). 1,2,3,4,7,8-Hexachlorodibenzodioxin (1,2,3,4,7,8-HxCDD), 1,2,3,6,7,8-Hexachlorodibenzodioxin (1,2,3,6,7,8-HxCDD), 2,3,7,8-Tetrabromodibenzofuran (2,3,7,8-TBrDF), 2,3,4,7,8-Pentabromodibenzofuran (2,3,4,7,8-PeBrDF), 3,3',4,4'-Tetrachlorinated biphenyl (PCB77) and 3,3'4,4'5,5'-Hexachlorinated biphenyl (PCB169) were purchased from Cambridge Isotope Laboratories, InC (USA). All other reagents (analytical reagent grade) were purchased from Sigma (USA). PCDD, PCDF, PCBs and benzene derivatives were dissolved in a solution of H_2O and N, N-dimethylformamide (V:V, 4:1) to prepare a series of standard solutions. The thiol-terminated DNA probe 5'-SH-$(CH_2)_6$-AGCTGCGTCACGCCCA-3' (the DNA probe from clone RP3-402G11 gene of human DNA sequence) and complementary sequence 5'-TGGGCGTGACGCAGCT-3' were synthesized by Takara Co. Ltd. (Dalian, China). The DNA stock solutions dissolved in 20 mmol L^{-1} Tris-HCl (pH 8.0) containing 100 mmol L^{-1} $MgCl_2$ and kept at -20 °C. Milli-Q water (18 MΩ cm) was used for all the experiments. Unless otherwise mentioned, phosphate buffer solution (PBS, 10 mM pH 7.0) containing 10 μmol L^{-1} MB (denoted as "MB solution") was used as the electrolyte in experiments.

2.2 Apparatus.

Cyclic voltammetry (CV) and differential pulse voltammetry (DPV) were carried out at gold electrode (diameter, 2 mm) using a CHI 440 Electrochemical Workstation (CHI Instruments Inc.). A three-electrode system consisted of a single-stranded DNA modified Au electrode (ssDNA/Au) or dsDNA/Au as the working electrode, Ag/AgCl

electrode (3M KCl) as the reference electrode and platinum wire as the auxiliary electrode.

2.3 Preparation and Characterization of ssDNA/Au and dsDNA/Au.

Prior to modification, the Au electrode surface was polished with slurries of alumina (1.0, 0.3, and 0.05 µm diameter successively) followed by rinsing thoroughly with Milli Q water. Then it was washed ultrasonically with ethanol followed by Milli-Q water three times respectively. Subsequently, it was cleaned electrochemically in 1 mol L^{-1} H_2SO_4 by potential scanning between 0 and 1.7 V until reproducible cyclic voltammograms were obtained. Thiolated DNA solution (15 µL, 2 µmol L^{-1}) was added onto the surface of cleaned Au electrode and kept at room temperature for 8 hours. The modified surface was then flushed with PBS (10 mmol L^{-1}) to remove the weakly adsorbed ssDNA. Finally, 1 mmol L^{-1} MCH was added onto the ssDNA surface for 1 hour to block the uncovered surface of the ssDNA/Au. The dsDNA/Au electrode was prepared by drop casting complementary DNA (15 µL, 2 µmol L^{-1}) onto the ssDNA/Au and kept for 2 hours at room temperature.

The ssDNA/Au or dsDNA/Au was characterized by cyclic voltammetry (CV) in MB solution. The MB solution was purged by high-purity nitrogen for 15 minutes and then CV was carried out at ssDNA/Au or dsDNA/Au from -0.5 to 0 V at 100 mV s^{-1}.

2.4 Screening and Estimation of Chemicals Genotoxicity Potential at dsDNA/Au.

Dioxins and dioxin-like chemicals were identified as genotoxic chemicals by International Agency for Research on Cancer (IARC). The genotoxicity screening ability of dsDNA/Au biosensor was evaluated by testing dioxins and dioxin-like

chemicals. 20 μL 2,3,7,8-TBrDF standard solution was placed onto the surface of the dsDNA/Au for 30 minutes. Then cyclic voltammetric scan was performed on the dsDNA/Au biosensor in MB solution.

More than 10 kinds of chemicals were evaluated for genotoxicity by the developed E-DNA biosensor at a certain concentration including dioxins, dioxin-like chemicals, PCBs, and benzene derivative. For a better comparison of tested chemicals, the decrease percentage of peak current (D_{pc}) is used to evaluate these analytes. The D_{pc} was calculated as follows: $D_{pc}= [(i_{MB}-i_t)/i_{MB}] \times 100\%$, *where* i_{MB} and i_t was the peak current of dsDNA/Au biosensor in MB solution before and after treatment with the target analyte.

2.5 Safety Considerations.

Dioxin, PCBs and benzene derivatives are carcinogenic agents. MSDS information for these chemicals should be consulted and precautions should be taken for handling them. Caution must be taken (i.e., wearing gloves, glass and mask) as the vapors of these chemical solutions are corrosive to eyes and skin.

3. Results and Discussion

3.1 Monitoring the Hybridization of DNA by E-DNA biosensor.

The hybridization efficiency is related to the sensitivity of the E-DNA biosensor. In this research, the hybridization process was monitored by electrochemical scanning in MB solution. MB as signal molecule could bind specifically to the guanine bases of ssDNA or readily intercalate into dsDNA[28]. The different binding modes of MB with ssDNA and dsDNA led to the changes in electrochemical response of ssDNA/Au,

before and after hybridization with complementary DNA. Figure 1 shows the CV of ssDNA/Au (curve a) and dsDNA/Au (curve b, after hybridization) in MB solution. MB has a strong affinity for the free guanine bases of ssDNA and hence a large amount of MB accumulates at ssDNA/Au surface, which results in a higher current signal (curve a, Figure 1). The CV current of MB on the ssDNA/Au decreased after hybridization with complementary DNA, which was due to the inaccessibility of guanine residues of ssDNA after hybridization and only those MB molecules which intercalated into dsDNA undergoes the redox process at the dsDNA/Au electrode[29, 30]. No peak was obtained at dsDNA/Au in 10 mmol L^{-1} PBS in absence of MB (Figure 1, curve c). Whereas, the peak current increased significantly in presence of MB indicating that MB bound to the ssDNA/Au or dsDNA/Au can easily achieve electron transfer.

Figure 2A shows the CV of dsDNA/Au in MB solution at different scan rates. The cathodic and anodic peak currents of MB increased linearly with the scan rates from 50 to 500 mV/s (Figure 2B). It reveals that the electron transfer between MB and working electrode was a surface-controlled electrochemical process and MB tightly intercalated into the dsDNA. The remarkable electrochemical response of MB on dsDNA/Au electrode indicates that the electron transfer through double helix was very efficient[31].

3.2 Genotoxicity Screening of 2,3,7,8-TBrDF.

2,3,7,8-TBrDF is a kind of halogenated persistent toxic chemical (a kind of bromide substituted dioxin) detectable at trace level in environment. Being an environmental

pollutant and carcinogen, its biological toxicology and environmental behavior have been preliminarily investigated[32, 33]. As it is well known that the toxic equivalency of dioxin is associated with mass concentration and toxic equivalency factor (TEF), different mass concentrations of 2, 3, 7, 8-TBrDF were detected by the prepared E-DNA biosensor. Figure 3 shows the DPV of 2, 3, 7, 8-TBrDF at dsDNA/Au biosensor using various concentrations. With the increase in concentration from 2 pg mL^{-1} to 1000 pg mL^{-1}, the DPV current of MB at dsDNA/Au biosensor decreases successively. A linear relationship was obtained between D_{pc} of the dsDNA/Au and the logarithm value of 2, 3, 7, 8-TBrDF concentrations (2 pg mL^{-1} to 1000 pg mL^{-1}), as shown in Figure 3B. The detection limit (S/N=3) for 2, 3, 7, 8-TBrDF was found as low as 0.7 pg mL^{-1} (i.e. 1.45 pmol L^{-1}). The calculated detection limit of this method is superior to the previously reported bioassay method for dioxin-like chemicals[34], demonstrating its good performance and potential as genotoxicity estimation tool for chemicals. The ultrasensitive response of E-DNA biosensor for 2, 3, 7, 8-TBrDF was mainly due to the interaction between 2, 3, 7, 8-TBrDF and dsDNA which was magnified by electroactive MB molecules. MB is an organic dye that belongs to the phenothiazine family and is a redox indicator with the formal potential of about -0.2 V (versus SCE) in neutral solution[35]. The oxidation potential of MB intercalation into dsDNA was at about -0.125 V, where interferences from possible co-existing chemicals were minimized. Besides, a compact-packed self-assembly monolayer of dsDNA and MCH was formed on the surface of Au electrode, which kept potential interferents away from the electrode surface. An ultrasensitive method for detection of

2, 3, 7, 8-TBrDF was developed which could be successfully applied for the *in vitro* estimation of chemicals genotoxicity. Considering the high sensitivity and short detection time (about 35 minutes), the proposed method can be an advantageous and alternative tool for *in vitro* screening of chemicals genotoxicity.

3.3 dsDNA/Au Performance for Identification of Chemicals Toxicity.

PCDD, PCDF (i.e. "dioxin") and co-planar PCBs (i.e. "dioxin-like chemicals") belong to the family of halogenated persistent toxic chemicals present at trace level in the environment. These chemicals have become a serious public health issue since they are known as the most toxic chemicals and can cause birth defects and cancer[36]. dsDNA/Au biosensor performance was assessed by applying successfully for *in vitro* genotoxicity screening of these chemicals. Table 1 summarizes the performance parameters of dsDNA/Au biosensor for the screening of 6 kinds of target analytes. The D_{pc} of dsDNA/Au biosensor for 10 pg mL^{-1} 1,2,3,4,7,8-HxCDD, 1,2,3,6,7,8-HxCDD, 2,3,7,8-TBrDF, 2,3,4,7,8-PeBrDF, 3,3',4,4'-TePCB (PCB77) and 3,3'4,4'5,5'-HxPCB (PCB169) was found 27%, 28%, 21%, 27%, 18% and 20%, respectively. The US Environmental Protection Agency (EPA) normalizes their toxicity to 2,3,7,8-TCDD, which has a TEF of 1.0[37]. The TEF values for 1,2,3,4,7,8-HxCDD, 1,2,3,6,7,8-HxCDD, PCB169 and PCB77 were 0.1, 0.1, 0.01 and 0.0001, respectively. The D_{pc} of 1,2,3,4,7,8-HxCDD (27%) was almost equal to that of 1,2,3,6,7,8-HxCDD (28%) but larger than that of PCB169 (20%) and PCB77 (18%). Interestingly, the results fit well with the TEF values of these compounds at the same concentration of 10 pg mL^{-1}. The obtained results show that the D_{pc} of

dioxins and PCBs mainly depended on their TEFs and concentrations. The D_{pc} of the E-DNA biosensor for 2, 3, 7, 8-TBrDF and 2, 3, 4, 7, 8-PeBrDF was 21% and 27%, respectively, which shows that the toxicity of these two brominated furan may be similar to these chlorinated dioxins. In fact, the preliminary studies have revealed that the toxicity of these brominated furans is similar to chlorinated dioxins[38, 39]. The results obtained demonstrate the E-DNA biosensor was a promising tool for predicating the potential toxicity of these chemicals. The developed E-DNA biosensor can be used effectively in the preliminary evaluation of the chemicals genotoxicity potential.

3.4 Application to Benzene Derivatives for Genotoxicity Potential Estimation.

The applicability of the developed E-DNA biosensor to estimate the genotoxicity of benzene derivative which are identified as potential genotoxic chemicals (e.g. hexachlorobenzene) was investigated. Table 2 illustrates genotoxicity evaluations for 2, 4-dinitrotoluene, chlorobenzene, p-dichlorobenzene, 1, 2, 3-trichlorobenzene and hexachlorobenzene (10 nmol L^{-1}) at dsDNA/Au biosensor. The order of D_{pc} found to be 2,4-dinitrotoluene (8.5%) < chlorobenzene (10%) < p-dichlorobenzene (18.9%) < 1,2,3-trichlorobenzene (24%) < hexachlorobenzene (29.9%). Above results show that, the D_{pc} increases with the increase in the number of chlorine atom of benzene derivative. A correlation was found between the response of the E-DNA biosensor and the genotoxicity of target chemicals. Previously, the toxicity of chemicals was predicted by the quantitative structure-activity relationship (QSAR) approach based on the photobacterium phosphoreum[40]. It revealed that the octanol:water partition

coefficients (lg Kow) was correlated well with the toxicity of chemicals[41]. The order of lgKow was 2,4-dinitrotoluene (1.98) < chlorobenzene (2.89) < p-dichlorobenzene (3.44) < 1,2,3-trichlorobenzene (4.05) < hexachlorobenzene (5.2), and the genotoxicity potential of the above chemicals showed a good consistency with the values of logKow[42]. The D_{pc} of these benzene derivatives at developed biosensor greatly matches with the toxicity potential of these analytes showing that dsDNA/Au biosensor has a great potential for rapid and efficient evaluation of the genotoxicity of chemicals, and it is in agreement with our previous study[43]. The biosensor response for mono-aromatic chemicals (e.g. 2840 pg mL^{-1} hexachlorobenzene with D_{pc} of 29.9%) is found to be two-order magnitude lower than coplanar dioxin (e.g. 10 pg mL^{-1} 1, 2,3,6,7,8-HxCDD with D_{pc} of 28.3%). It could be deduced from the results that the toxicity of mono-aromatic chemicals is much lower than that of dioxins chemicals which is reasonable as dioxins are known to be most toxic chemicals.

The genotoxicity estimation ability of biosensor was also evaluated by many other chemicals including potassium nitrate, sodium citrate, sodium oxalate, urea, ethyl acetate, ethanol, formamide, N, N-dimethylformamide, diethyl carbonate and dichloroethane at a high concentration of 100 ng mL^{-1}. The D_{pc} of biosensor for these chemicals were within 5%. According to the genotoxicity research of the above chemicals by IARC, these chemicals do not have genotoxicity effect. On the basis of results obtained for different analytes at E-DNA biosensor, D_{pc} less than 5% was defined as a non-genotoxic screening result. Thus the E-DNA biosensor can efficiently identify and estimate genotoxicity potential of the chemicals as exemplify

by Dioxins (PCDD， PCDF， brominated-furan), PCBs, chlorinated benzene, etc. The developed dsDNA/Au biosensor can be a promising tool for in vitro screening of chemicals genotoxicity.

4. Conclusions

In the present work, a new strategy based on an electrochemical DNA biosensor has been proposed for the rapid estimation of chemicals genotoxicity potential with significantly sensitive feedback. The E-DNA biosensor was successfully applied for genotoxicity screening of Dioxin and dioxin-like chemicals which are identified halogenated genotoxic chemicals. The biosensor displayed concentration-dependant response for dioxin and dioxin-like chemicals with a low detection limi. The proposed biosensor provided a novel and powerful tool for rapid *in vitro* screening of genotoxicity potential of chemicals and could be an attractive candidate to fulfill the challenges of genetic toxicology testing in the 21st century.

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Figure

Figure 1. Cyclic voltammetry of the ssDNA/Au in 10 mmol L^{-1} PBS (pH 7.0) containing 10 μmol L^{-1} MB before (a) and after (b) hybridization with 2 μmol L^{-1} complementary DNA. Curve c is the response signal of dsDNA/Au in PBS buffer saline in the absence of MB.

Figure 2 (A) Cyclic voltammogram of dsDNA/Au after incubation of 10 μmol L^{-1} MB in 10 mmol L^{-1} PBS buffer (pH 7.0). Scan rate from inner to outer: 50, 100, 200, 300, 400, 500 mV s^{-1}. (B) Plot of reduction peak current vs. scan rate.

Figure 3. (A) Differential pulse voltammograms of the dsDNA/Au biosensor at different concentrations of 2,3,7,8-TBrDF from 2 pg mL^{-1} to 1000 pg mL^{-1}. Pulse amplitude, 50 mV; pulse period, 0.2 s. (B) The decrease percent of peak current vs. the log value of 2,3,7,8-TBrDF concentration.

Table 1. Genotoxicity screening of dioxins and its analogue by dsDNA/Au biosensor.

Table 2. Genotoxicity Evaluation of Chemicals by dsDNA/Au Biosensor.

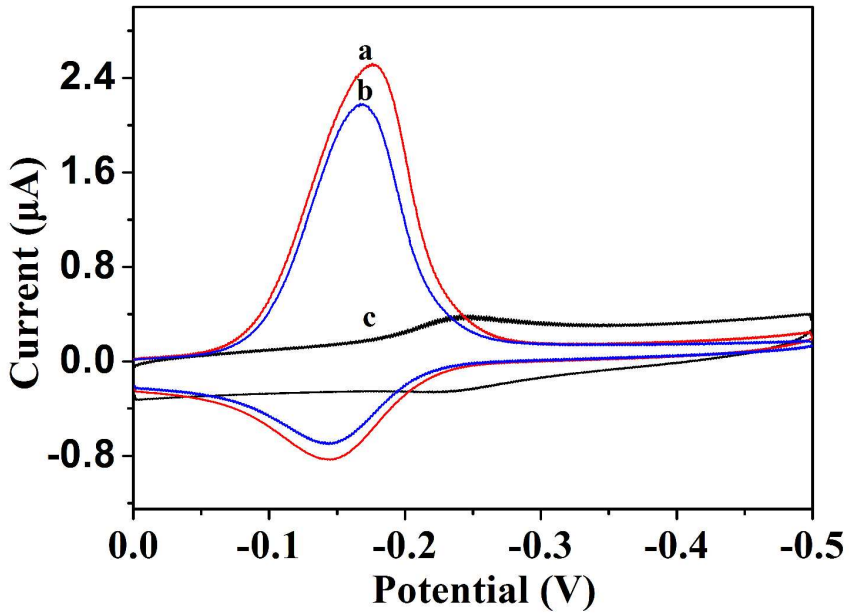


Figure 1.

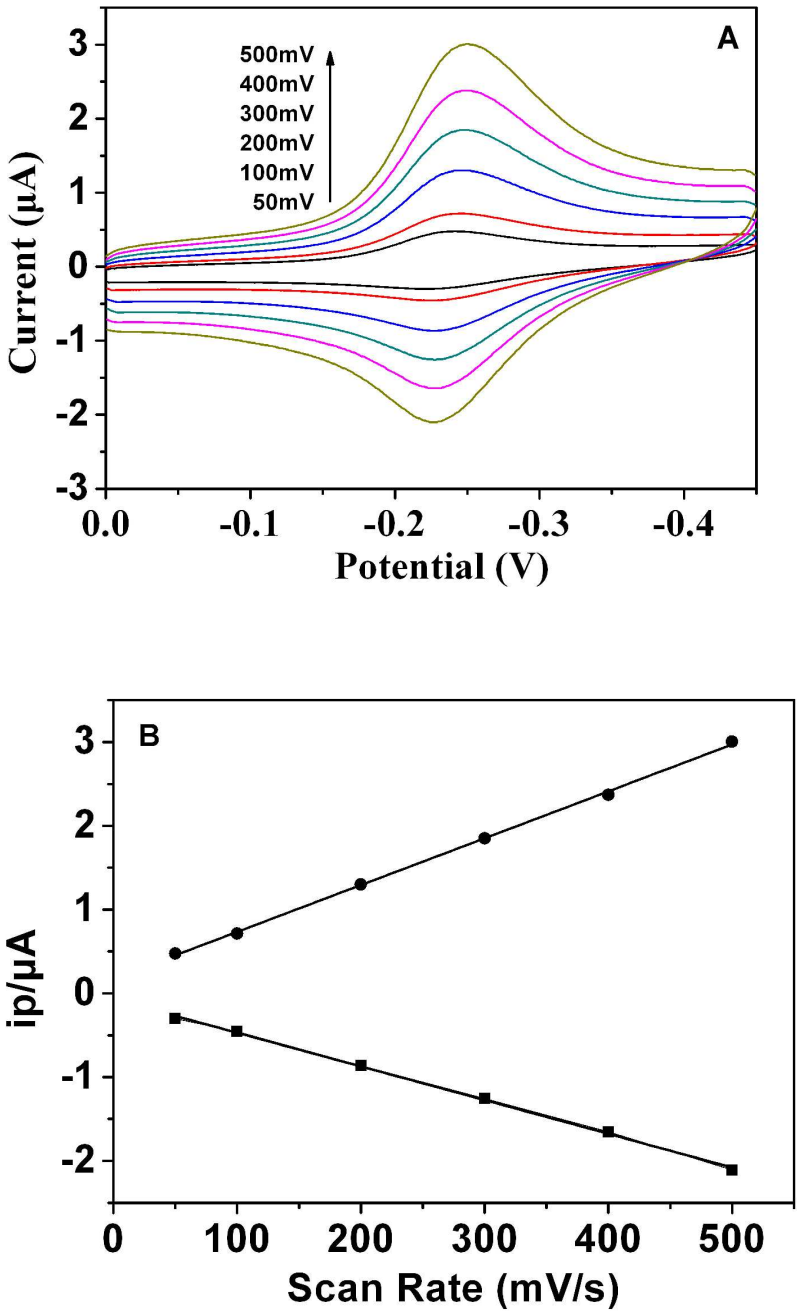


Figure 2

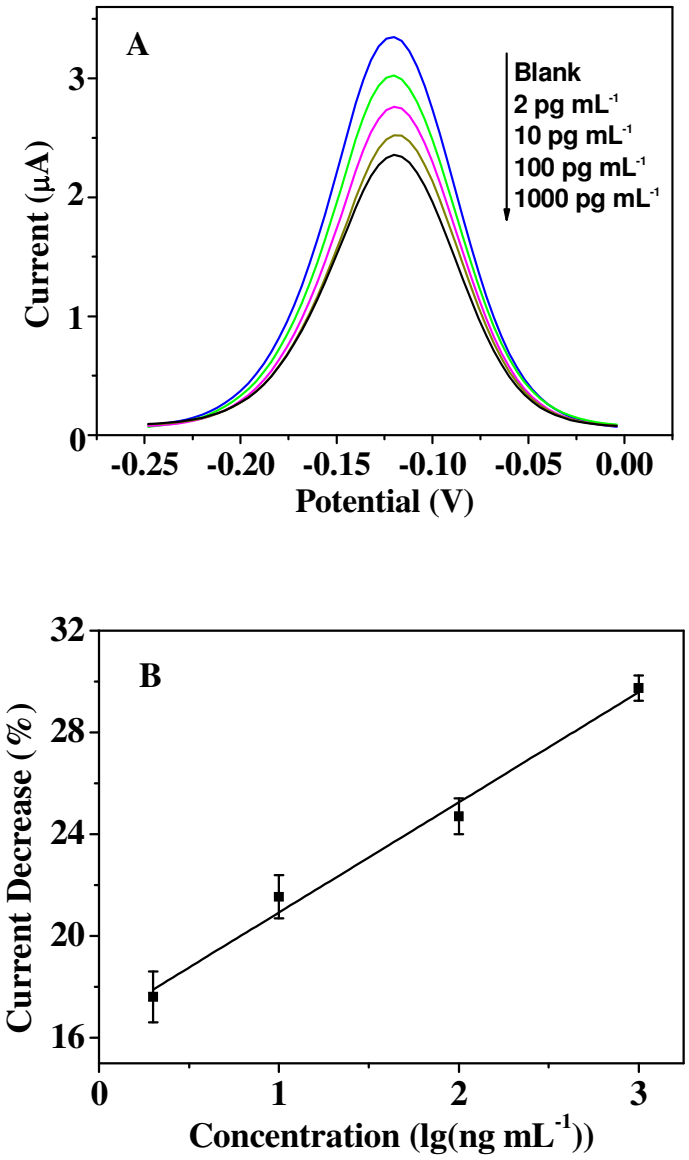


Figure 3.

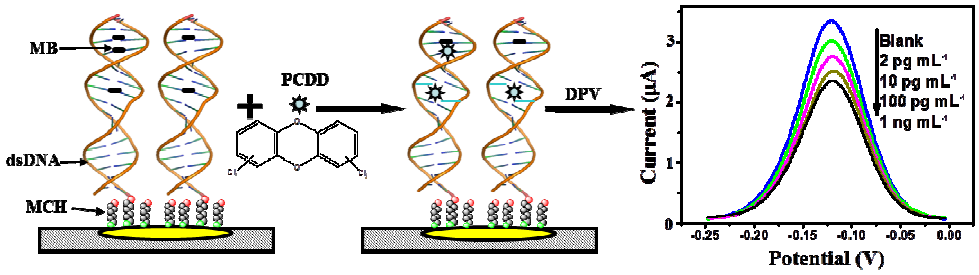
Table 1. Genotoxicity screening of dioxins and its analogue by dsDNA/Au biosensor.

Targets	Detection limit (pg mL^{-1})	Linear range (pg mL^{-1})	D_{pc} (10 pg mL^{-1})	RSD	TEF
1,2,3,4,7,8-HxCDD	0.7	2-1000	27.3%	0.1	0.1
1,2,3,6,7,8-HxCDD	0.3	1-100	28.3%	0.7	0.1
3,3',4,4'-TePCB	3.0	10-100	18.1%	1.0	0.0001
3,3',4,4',5,5'-HxPCB	0.7	2-100	19.8%	0.1	0.01
2,3, 7,8-TBrDF	0.7	2-1000	21.5%	0.1	x
2,3, 4,7,8-PBrDF	0.7	2-100	27.2%	0.9	x

Note: x means no established TEF was provided up to date.

Table 2. Genotoxicity Evaluation of Chemicals by dsDNA/Au Biosensor.

Target (concentration: 10 nmol L^{-1})	D_{pc}	Octanol-water partition coefficient (Log Kow)
2,4-dinitrotoluene	8.5%	1.98
chlorobenzene	10%	2.89
p-dichlorobenzene	18.9%	3.44
1,2,3-trichlorobenzene	24%	4.05
hexachlorobenzene	29.9%	5.20



Graphical abstract: Schematic diagram of the E-DNA biosensor detection of PCDD by DPV.