Original scientific paper

Application of a cobalt(II) coordination complex in the electrochemical detection and quantification of adrenaline

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Abstract

Adrenaline, also known as epinephrine, is a hormone and neurotransmitter produced by the adrenal glands. In the bloodstream, adrenaline affects vital physiological functions such as heart rate, blood pressure and glycogen breakdown. Abnormal adrenaline levels can indicate underlying health disorders, with increases often seen in emotional or physical stress and diseases such as cancer and Parkinson's disease. Electrochemical methods are effective for detecting neurotransmitters, as they are fast-responding, easy to use, and highly sensitive. In this context, a novel electrochemical sensor has been developed for the precise and selective detection of adrenaline. The sensor, based on a glassy carbon electrode modified with a cobalt(II) coordination complex, showed improved electrochemical performance for adrenaline detection, with a linear response range of 0.1 to 2.0 µM, a detection limit of 0.09 µM, and a sensitivity of 26.92 nA µM^{-1}. When analysing real samples, the modified electrode showed favourable electroanalytical properties for the oxidation of adrenaline and demonstrated stability, reproducibility and suitability for use in pharmaceutical formulations. The selectivity of the sensor was confirmed by interference studies, which showed negligible response changes in the presence of common interferents, except for ascorbic acid (vitamin C).

Keywords

Electrochemical sensor; epinephrine, modified glassy carbon; metal ion complex; pharmaceutical sample

Introduction

Adrenaline (AD) is a sympathetic neurotransmitter and a hormone secreted by the adrenal medulla that performs numerous physiological functions, including the regulation of blood pressure, vasoconstriction and heart rate, and acts as a bronchodilator in asthma. It has long been used in medical interventions such as cardiopulmonary resuscitation, defibrillation and the treatment of cardiac arrest [1,2]. AD is typically released during physical (*e.g.* muscular exertion, thermal burns) or emotional (*e.g.* trauma) stress, which activates the sympathoadrenal system and leads to increased levels of AD in the blood and urine [3-5]. It also plays an important role in stress-related

disorders such as anxiety and depression [6]. In addition to stress, various external factors such as the consumption of certain foods, including coffee, tea, bananas, chocolate and citrus fruits, as well as certain medications, can also increase urinary AD levels, which are typically between 1 nM and 1 μM. However, excessive or abnormal exposure to AD can lead to adverse effects such as tremors, anxiety and sweating [7]. In addition, reduced AD levels have been observed in patients with Parkinson's disease [8]. Therefore, the ability to accurately monitor AD with reliable and cost-effective analytical methods is of great importance. As a catecholamine, AD is electrochemically active and therefore lends itself to quantification using electroanalytical methods. These methods have attracted considerable research interest due to their simplicity, affordability and ability to provide rapid analytical results [9-12]. Despite these advantages, the detection of AD in real biological matrices remains a challenge due to its typically low concentration (in the micromolar range) and its short lifetime in the extracellular environment. In addition, the oxidation potential of AD strongly overlaps with that of other endogenous biomolecules, leading to signal interference and reduced selectivity in electrochemical measurements [13]. To address these limitations, most AD sensors use modified carbon-based materials that offer higher sensitivity, selectivity and surface area for better detection [14-17]. These materials also allow the incorporation of various electro-active modifiers [18]. To meet the basic requirements for electrochemical activity, namely low resistivity and high carrier mobility, cobalt(II) coordination compounds, which are well-researched and commonly used in applications such as supercapacitors [19-25] and semiconductors [26,27], are promising candidates for sensor development [28-31]. Co–organic frameworks have gained significant attention due to their structural stability, conductivity, and impressive theoretical capacitance [24]. In the present work, we report the electrochemical characterization of a prepared cobalt(II) coordination compound used to modify a glassy carbon electrode (GCE) for the purpose of selective and sensitive detection of adrenaline (Scheme 1).
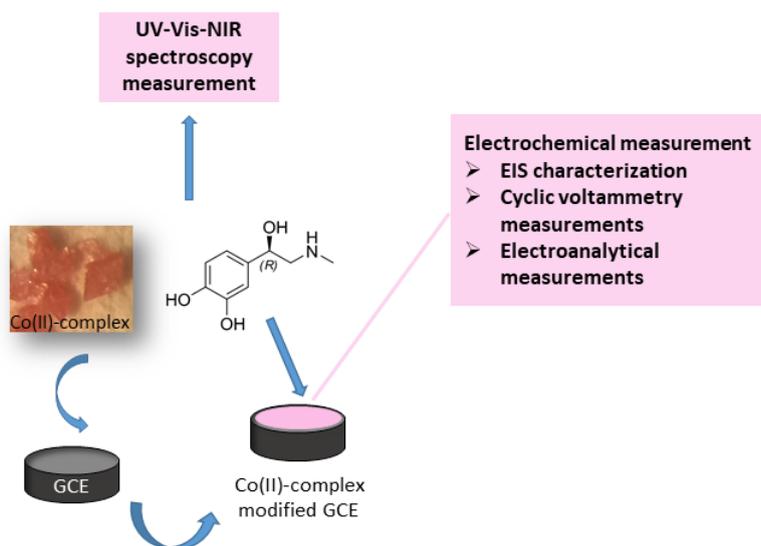
Scheme 1. *Schematic representation of the application of a cobalt(II) coordination complex for the electrochemical detection and quantification of adrenaline*

Experimental

Materials

The coordination compound Co(II), {[Co(1,2-bpe)$_2$(H$_2$O)$_2$](6-NH$_2$nic)(NO$_3$)4H$_2$O}$_n$ was prepared by the method of hydrothermal conditions described in the work of Kukovec e*t. al.* [29], as the reaction produces crystals of the ligand at normal pressure and room temperature. Cobalt(II) nitrate hexa-

hydrate, 6-aminonicotinic acid and 1,2-bis(4-pyridyl)ethane were mixed in a molar ratio of 1:2:1 in aqueous and ethanolic solutions. After the pH was adjusted to 7 with NaOH, the mixture was heated to 130 °C for 72 hours in a Teflon-lined autoclave and then cooled to room temperature for 24 hours. The solution was filtered and evaporated at room temperature for about 25 days, forming pink crystals.

A suspension of the complex was applied to the prepared GCE. The suspension was prepared by dispersing 3 mg of the Co(II) coordination compound $\{[Co(1,2\text{-bpe})_2(H_2O)_2](6\text{-NH}_2\text{nic})(NO_3)4H_2O\}_n$ in 300 μL of *N,N*-dimethylformamide (DMF) in an ultrasonic bath. The resulting suspension was applied to the GCE surface with a semi-automatic pipette (20 μL) and dried in an oven at 50 °C for 30 min.

The analyte used was a 1 mM solution of DL-adrenaline hydrochloride, prepared by weighing out 2.2 mg of adrenaline, transferring it to a 10 mL volumetric flask, and making up to the mark with distilled water.

A 0.2 M phosphate buffer solution with a pH of 7.4 was used as the basic electrolyte (45 mL of 0.2 M NaOH was added to 100 mL of KH_2PO_4, pH 4.5).

Spectroscopic measurement

Transmission electron microscopy (TEM) was used to morphologically characterize the GCE modified with the Co(II) coordination compound $\{[Co(1,2\text{-bpe})_2(H_2O)_2](6\text{-NH}_2\text{nic})(NO_3)4H_2O\}_n$. The particles of the Co(II) complex compound are voluminous and uniformly agglomerated, resulting in a uniform surface of the modified GCE (Figure 1).
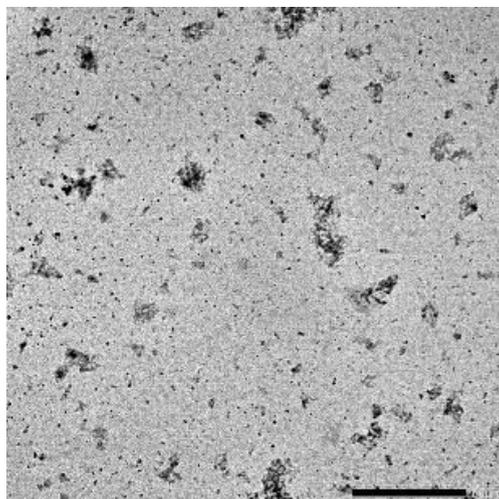

Figure 1. *TEM image of GCE modified with Co(II) complex. Scale bar = 1 μm*

The electrochemical impedance spectroscopy measurements were performed using a Solartron SI 1287 interface and a Solartron SI 1255 frequency response analyser. EIS measurements of unmodified GCE and GCE modified with Co(II) compounds were performed in the frequency range from 100 kHz to 0.1 Hz at open circuit potential (E_{ocp}).

For the UV-Vis absorbance measurement, a cuvette was filled with 400 μL DMF and 100 μL of a suspension of the Co(II) coordination compound in DMF. A 1 mM adrenaline solution was then added to the cuvette in portions up to a total volume of 3 mL, and the absorbance was recorded at a fixed wavelength of 350 nm.

Electrochemical measurements

A glassy carbon electrode (GCE) in the form of a cylinder with a geometric base area of 0.126 cm^2 in a Teflon body was used as the working electrode. A platinum wire served as a counter electrode and an Ag / AgCl / 3 M KCl electrode, the so-called silver/silver(I) chloride electrode, was used as a

reference electrode. Before each measurement, the GCE electrode is prepared as follows: a) mechanically - grinding with papers of prescribed fineness (1200, 1500, 3000) in circular movements while simultaneously moistening with water; b) polishing - aluminium(III) oxide paste 1 μm and 0.05 μm and c) degreasing - ethanol (96 %) in an ultrasonic bath for 3 minutes.

All cyclic voltammetry measurements were performed with a standard three-electrode cell. The device consisted of a potentiostat (Autolab PGSTAT 302N) connected to a personal computer controlled by GPES 4.9 software (Eco Chemie, Eco Utrecht, The Netherlands). Cyclic voltammograms of unmodified and cobalt(II) complex-modified GCE with different concentrations of adrenaline (0 to 100 μM) in 0.2 M PB (pH 7.4) were recorded in the potential range from -0.4 to 0.5 V *versus* Ag|AgCl at a scan rate of 25 mV s^{-1}. A 0.2 M PB (pH 7.4) is a phosphate buffer solution prepared by adding 45 mL of 0.2 M NaOH to 100 mL of KH_2PO_4 solution (pH 4.5).

For the quantitative analysis of AD on Co(II)-complex-modified GCE, the differential pulse voltammetry (DPV) method was chosen because it is more sensitive and has a lower detection limit than CV. Various parameters (accumulation potential, E_{acc}, accumulation time, t_{acc}, pulse amplitude, ΔE_p and step potential, ΔE_s) were optimized to develop an electrochemical method for the determination of adrenaline. All experiments were performed from -150 to 500 mV, E_{acc} = -150 mV, t_{acc} = 30 s, ΔE_p = 25 mV and ΔE_s = 4 mV.

Adrenaline bitartrate ampules supplied by PARCOTIC for infusion at a concentration of 1 mg/1 mL were used as the real sample for the determination of adrenaline. The infusion ampoule was diluted with a basic electrolyte (200 μL of a real adrenaline sample of unknown concentration was added to 100 mL buffer). The analysis was performed according to the standard addition method and 1 mM adrenaline solution was added.

Results and discussion

Characterization of the Co(II) coordination compound

The structure representing the asymmetric unit of the compound is described in detail in [29]. It consists of a cobalt(II) ion, two coordinated 1,2-bis(4-pyridyl)ethane-(1,2-bpe) ligands, two coordinated water molecules, a 6-aminonicotinate anion, a nitrate ion and four lattice water molecules. In the polymeric cationic unit {[Co(1,2-bpe)$_2$(H$_2$O)$_2$]$^{2+}$}$_n$, the cobalt(II) ion has an octahedral coordination geometry and is bound to the nitrogen atoms of four different 1,2-bpe ligands and two water molecules in the trans position.

Electrochemical impedance spectroscopy characterization

The electrochemical behaviour of unmodified and Co(II)-modified glassy carbon electrode (GCE) in the presence of adrenaline was investigated using electrochemical impedance spectroscopy (EIS). The results are presented in the form of Nyquist diagrams (Figure 2) and Bode diagrams (Figure 3). For the unmodified GCE (Figure 2a), a significant reduction in the diameter of the capacitive semi-circle is observed with increasing adrenaline concentration, indicating a decrease in the total impedance of the system. This suggests that the oxidation of adrenaline at the electrode surface is facilitated, as the decrease in the resistance component is generally associated with improved electron transfer kinetics [32].

In contrast, the Nyquist plots for the Co(II)-modified GCE (Figure 2, right) also show a decrease in the semicircle diameter with increasing adrenaline concentration, although the impedance spectra are clearly different from those of the unmodified electrode, suggesting different interfacial processes.
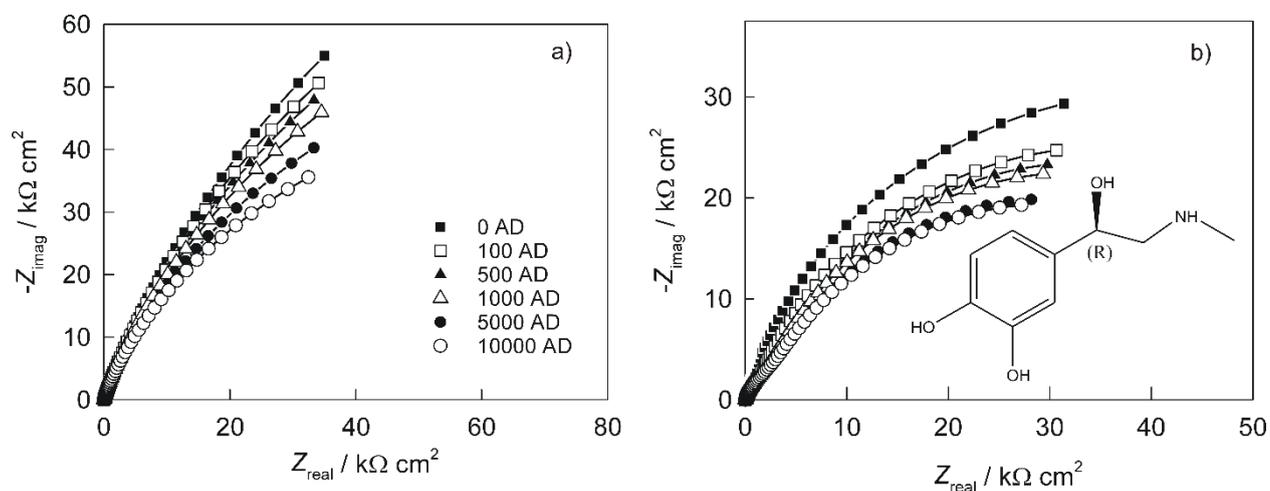
Figure 2. *a) Nyquist plots of the impedance spectra of unmodified GCE and b) Co(II)-complex-modified GCE, in 0.2 M PB pH 7.4, with different concentrations of AD. Inset: chemical structure of adrenaline (epinephrine)*

After adsorption and coordination of adrenaline to the Co(II) centres on the modified GCE surface, a transient Co(II)-adrenaline complex was formed, which facilitates electron transfer during the oxidation of adrenaline and improves charge transfer due to better conductivity and surface reactivity.
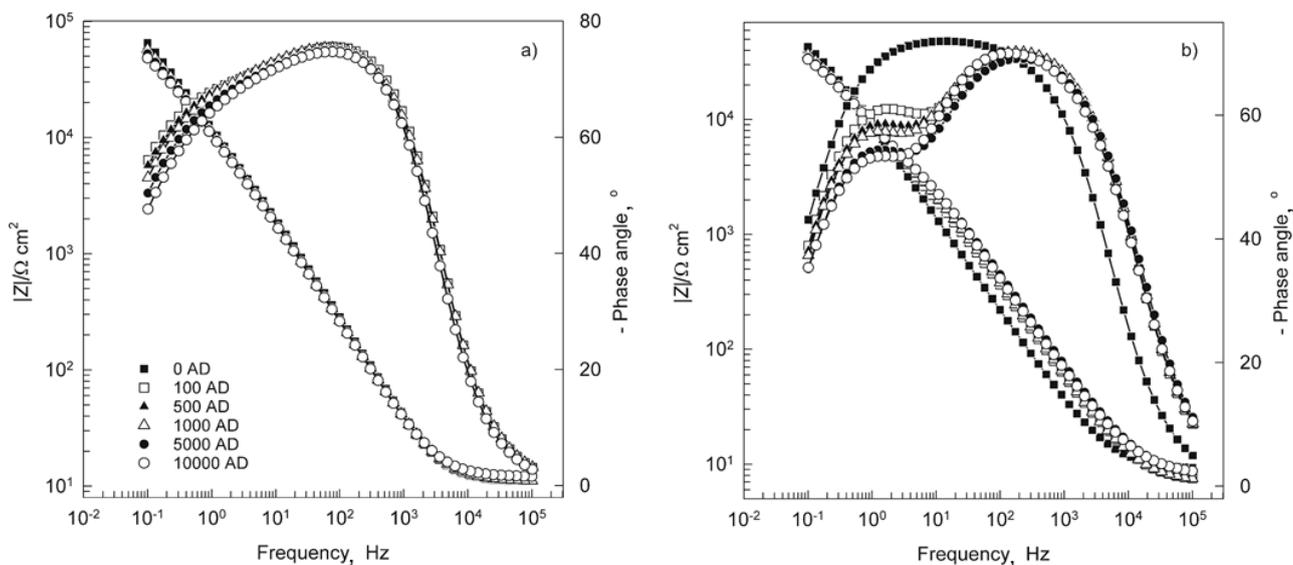

Figure 3. *a) Bode plots of the impedance spectra of unmodified GCE and b) Co(II)-complex-modified GCE, in 0.2 M PB pH 7.4, with different concentrations of AD*

To better understand these observations, the electrical equivalent circuits (EECs) shown in Figure 4 were fitted to measured impedance spectra. The EEC models used consist of two constant phase elements (CPE_1 and CPE_2), two resistive components (R_1 and R_2) and the electrolyte resistance (R_{el}). Together, they represent the total impedance of the working electrode, encompassing the interface between the electrode and electrolyte, as well as the uncompensated solution resistance [33,34]. In both models, the elements R_2/CPE_2 describe the most important faradaic charge transfer process at the electrode surface. The elements R_1/CPE_1 take into account additional interfacial phenomena, such as double-layer effects, surface heterogeneities, or adsorption processes. For the unmodified GCE, the impedance response suggests a simpler interfacial process that is well described by a dominant *R*-CPE branch with a secondary contribution. For the modified GCE, the more complex model with two parallel *R*-CPE branches reflects the coexistence of direct electron transfer and specific interactions between adrenaline and Co(II) centres, such as coordination or transient complex formation.
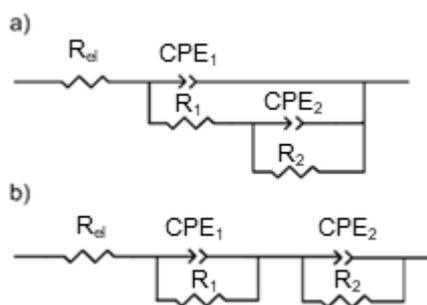
***Figure 4**. Electrical equivalent circuits used for the EIS analysis for: a) unmodified electrode and b) Co(II)-modified electrode*

The primary objective was to compare the effect of electrode modification on the electro-chemical response to increasing adrenaline concentrations, particularly in relation to the kinetics of the oxidation reaction. As with the unmodified GCE, the Co(II)-modified electrode showed a reduction in the semicircle diameter in response to increased adrenaline concentration, which is associated with an enhancement in electron transfer. The observed impedance behaviour suggests the possibility of specific interactions between the Co(II) complex and adrenaline at the electrode surface. These interactions likely lead to the formation of Co(II)-adrenaline complexes, which could facilitate the oxidation reaction and thereby reduce the overall impedance [35,36]. The quantitative fitting parameters derived from the EIS spectra are summarized in Tables 1 and 2. Table 1 contains the values of the EEC elements (R_1, R_2, Q_1, Q_2) for the unmodified GCE, while Table 2 shows the corresponding parameters for the Co(II)-modified electrode. Q_1 and Q_2 represent the parameters of the constant phase elements CPE_1 and CPE_2, respectively, while n_1 and n_2 are corresponding CPE exponents ($0 \leq n \leq 1$).

***Table 1**. Equivalent circuit parameters obtained by fitting for unmodified GCE in 0.2 M PB pH 7.4*

$10^5 \times Q_1$ / Ω^{-1} cm^{-2} s^n	n_1	R_1 / Ω cm^2	$10^6 \times Q_2$ / Ω^{-1} cm^{-2} s^n	n_2	R_2 / kΩ cm^2	V_{AD} / µL
1.16	0.886	6974	9.46	0.637	314.8	0
1.21	0.886	6192	10.11	0.624	272.9	100
1.28	0.881	5323	10.26	0.590	269.8	500
1.32	0.877	7967	10.10	0.580	225.9	1000
1.27	0.883	5002	11.94	0.578	184.9	5000
1.30	0.881	4569	12.99	0.558	154.4	10000

R_{el} = 11 Ω cm^2

***Table 2**. Equivalent circuit parameters obtained by fitting for GCE modified with cobalt(II) complex in 0.2 M PB pH 7.4*

$10^5 \times Q_1$ / Ω^{-1} cm^{-2} s^n	n_1	R_1 / Ω cm^2	$10^6 \times Q_2$ / Ω^{-1} cm^{-2} s^n	n_2	R_2 / kΩ cm^2	V_{AD} / µL
17.49	1.000	1796	2.76	0.800	80.7	0
3.27	0.848	805	2.51	0.793	69.8	100
3.05	0.832	1327	2.63	0.798	64.9	500
2.73	0.836	1570	2.68	0.800	61.9	1000
2.08	0.851	1576	2.75	0.772	57.3	5000
2.75	0.902	1580	2.87	0.759	57.2	10000

R_{el} = 8 Ω cm^2

In both cases, the value of R_2, which is typically associated with charge transfer resistance, systematically decreases with increasing adrenaline concentration. This trend supports the hypothesis of increased catalytic activity at higher adrenaline levels and suggests possible surface phenomena such as adsorption or complex formation that influence impedance behaviour [30].

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UV-Vis-NIR spectroscopy measurement

Figure 5 shows the dependence of the absorbance (A) on the molar ratio of AD to cobalt(II) ions ($[AD]/[Co^{2+}]$). The absorbance increases linearly with the molar ratio until a maximum is reached, indicating complex formation. Beyond this point, the absorbance decreases, indicating that the coordination sites on Co^{2+} are saturated and excess AD does not contribute to further complex formation. This behaviour is characteristic of the molar ratio method used to determine complex stoichiometry [37].
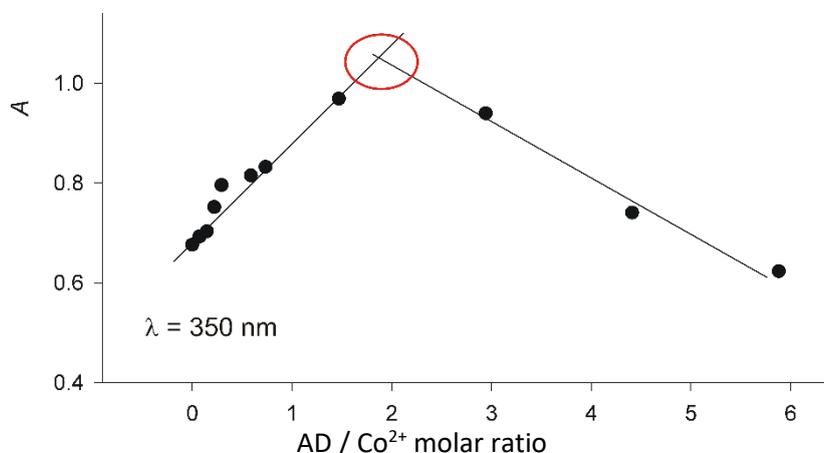

Figure 5. *Graphical representation of the dependence of absorption on the molar ratio of the reactants*

At the point of intersection (maximum absorbance A = 1.05214), the AD / Co^{2+} molar ratio is ≈2, indicating a stoichiometric ratio of Co^{2+} to AD of 1 : 2, Equation (1):

$$Co^{2+} + 2AD \leftrightarrow [Co(AD)_2]^{2+} \tag{1}$$

Since the total Co^{2+} reacted at A_{max} (c_{read} = 0.473 mM), the formation constant (K_f) of the complex was calculated using the absorbance data: K_f = 41372.02 M^{-2}.

This high value indicates strong binding between Co^{2+} and adrenaline molecules, which is associated with stable complex formation [38].

Cyclic voltammetry measurements

Cyclic voltammograms of unmodified and cobalt(II) complex-modified GCE with different concentrations of adrenaline (0 to 100 μM) in 0.2 M PB (pH 7.4) were recorded in the potential range from -0.4 to 0.5 V against Ag|AgCl at a scan rate of 25 mV s^{-1} (Figure 6).
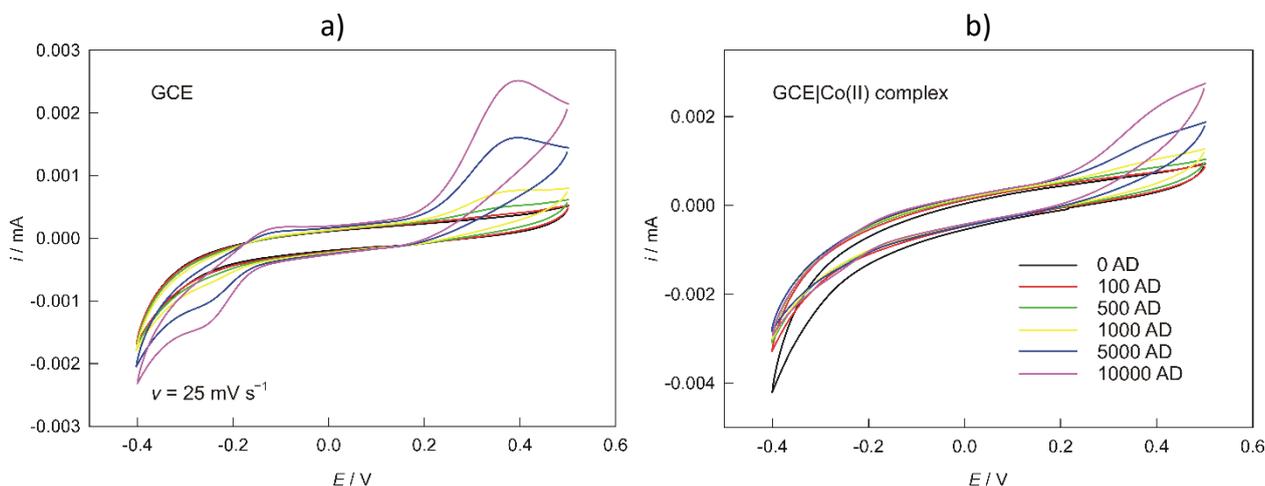

Figure 6. *a) Cyclic voltammograms recorded at unmodified GCE and b) Co(II)-complex-modified GCE in 0.2 M PB pH 7.4, with different AD concentrations added to the basic electrolyte. v = 25 mV s^{-1}*

The oxidation current increases with increasing adrenaline concentration, indicating a concentration-dependent electrochemical reaction. The presence of the Co(II) complex on the electrode surface facilitates the adsorption of adrenaline from the solution, which probably leads to the formation of a surface-bound $[Co(AD)_2]^{2+}$ complex [39]. The initial potential for the oxidation of adrenaline at the modified electrode is anodically shifted by about 20 mV compared to the unmodified electrode, indicating altered electron transfer kinetics due to the surface modification [40]. In addition, the oxidation peak at the modified electrode is less pronounced, indicating altered reaction kinetics possibly related to complex formation at the electrode interface.

The slower kinetics support the hypothesis that adrenaline binds to the Co(II) complex immobilised at the surface and thus alters the dynamics of electron transfer [41]. This interaction between the Co(II) complex and epinephrine indicates some degree of molecular recognition, indicating a possible "lock-and-key" selectivity of the electrode for epinephrine [32].

To evaluate the processes occurring at the electrode surface, the influence of the scan rate on the current maxima was investigated. Figure 7 shows the cyclic voltammograms of the Co(II) complex-modified GCE in a basic electrolyte with analyte (10 μM AD) at different scan rates.
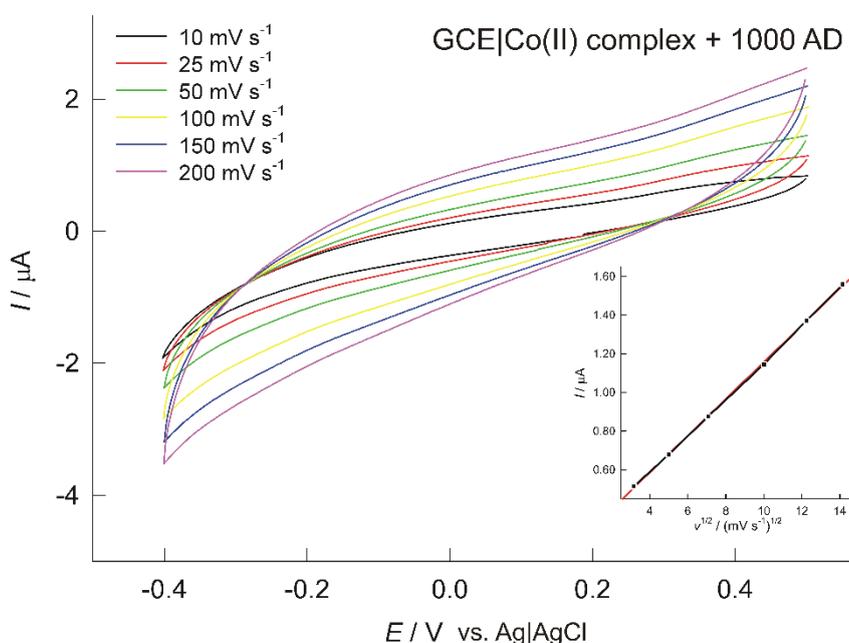

Figure 7. *Cyclic voltammogram recorded at Co(II)-complex-modified GCE in 0.2 M PB, pH 7.4 with analyte (10 μM AD) at different scan rates. Inset: change in peak current (at* E *= 258 mV) versus scan rate*

With an increasing scan rate, the cyclic voltammogram exhibits a "broadening effect," accompanied by an increase in both cathodic and anodic current densities. This behaviour reflects the pseudocapacitive nature [18-19,22] of the Co(II) complex. In addition, the redox peaks shift to more positive and negative potentials with increasing scan rates, indicating kinetic limitations in the electron transfer process. At higher scan rates, the limited time available for the analyte to interact with the active sites on the modified electrode results in greater separation of the peaks. This indicates that the catalytic activity of the electrode towards epinephrine is more pronounced at lower scan rates when sufficient time is available for surface reactions [18].

The insert in Figure 7 shows the dependence of the current recorded at 258 mV against Ag|AgCl on the root of the scan rate. The dependence of the current on the scan rate can be used to determine whether the process at the electrode is diffusion-controlled, *i.e.* whether the rate of the electrochemical reaction is limited by the speed at which the reactant reaches the surface of the electrode.

The diagram illustrates a linear dependence, indicating that it is a diffusion-controlled reaction [6,42]. The considerations led to the conclusion that the correct optimization of the parameters of differential pulse voltammetry can be used to selectively bind adrenaline to the Co(II) complex and that the modified electrode can be used to determine the concentration of adrenaline in the sample.

Electroanalytical measurements

For the quantitative analysis of AD on Co(II)-complex-modified GCE, the DPV method was chosen because it is more sensitive and has a lower detection limit than CV. Various parameters (accumulation potential, E_{acc}, accumulation time, t_{acc}, pulse amplitude, ΔE_p and step potential, ΔE_s) were optimized to develop an electrochemical method for the determination of adrenaline (not shown here). Figure 8 shows the DPV results obtained at the GCE modified with Co(II) complexes in 0.2 M PB, pH 7.4. The continuous addition of adrenaline results in an increase in the anodic peak current, indicating the electrocatalytic activity of the modified electrode. In this potential range, the observed process corresponds to the oxidation of adrenaline [3,6,18,42]. The DPV voltammograms shown are corrected for the current of the Co(II) complex, as Co(II) forms a complex with adrenaline, which was detected spectrophotometrically. The corresponding calibration curve, shown as an inset in Figure 8, showed a linear relationship between the adrenaline oxidation current and the adrenaline concentration with a sensitivity of 26.92 nA μM^{-1}.

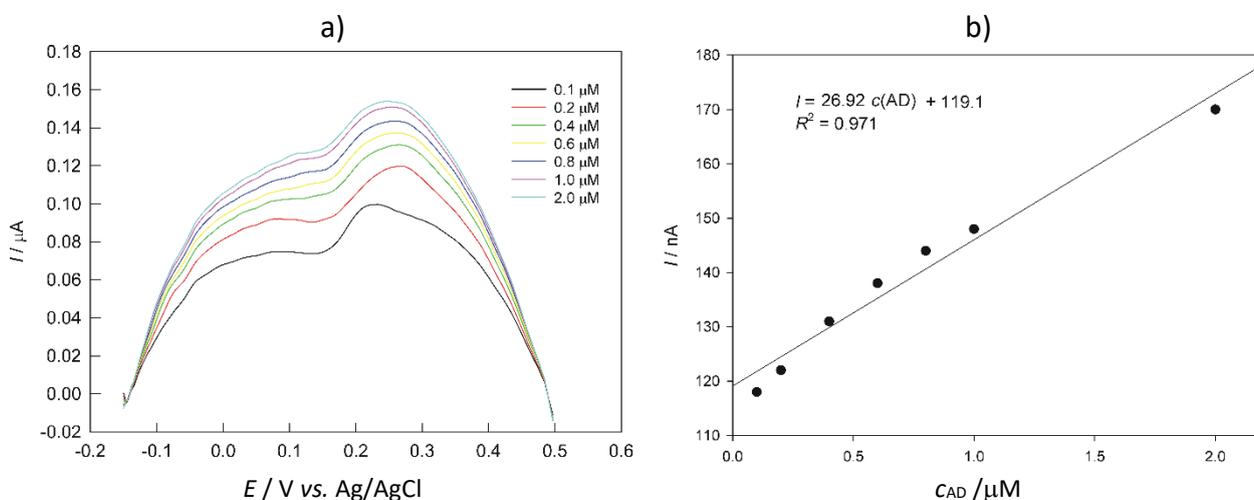**Figure 8.** *a) DPVs (conditions: E_{acc} = -150 mV, t_{acc} = 30 s, ΔE_p = 25 mV, ΔE_s = 4 mV) for the oxidation of adrenaline, recorded at GCE|Co(II)complex with "subtract disk file" correction in 0.2 M PB, pH7.4 for the AD concentrations tested, and b) calibration plot for the selected concentration range of AD*

Selectivity is a key parameter in the development of electrochemical sensors, particularly due to the potential overlap in oxidation potentials between the target analyte and common interfering species [3,42]. In this study, the selectivity of a GCE modified with Co(II) complexes was evaluated by examining the influence of various potential interferents on the current responses, including: folic acid (FA), glycine (Gly), urea (UA), lauric acid (LA), malonic acid (MA), citric acid (CA) and vitamin C (VitC), each added in a 1000-fold molar excess over 0.01 mM adrenaline (1:1000), except for vitamin C, which was present at a 50-fold higher concentration than AD (1:50). DPV measurements were performed to evaluate the current responses, as both sensitivity and selectivity are critical for accurate and reliable adrenaline detection (Figure 9). These values were obtained after applying the "subtract disk file" correction, whereby the current response of the Co(II) complex alone (*i.e.* without the analyte) was subtracted from both measurements - those recorded without interferents and those recorded in the presence of interferents. The presence of these substances resulted in

only minor changes in the voltammetric profile without significantly affecting the peak current associated with adrenaline oxidation. Among the interfering substances tested, vitamin C showed a more pronounced effect, probably due to its strong adsorption affinity, which led to a partial surface blockade of the modified electrode. Nevertheless, the electrode modified with the GCE|Co(II) complex showed satisfactory selectivity towards adrenaline under the conditions tested, indicating its potential applicability in complex sample matrices.
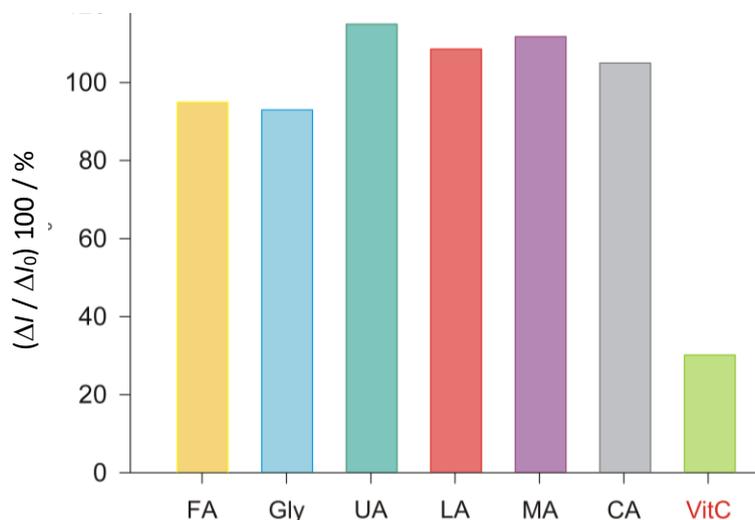

***Figure 9**. Relationship between interference current (ΔI) and adrenaline current (ΔI_0) at the GCE|Co(II) complex in the basic electrolyte*

The reproducibility was evaluated using five independently prepared GCEs modified with cobalt(II) complexes over five days and resulting in a relative standard deviation of 4.8 %.

After optimizing the experimental conditions and characterizing the sensor, the developed analytical system was applied to the determination of adrenaline in a real pharmaceutical sample to evaluate its practical applicability. The analysis was performed on adrenaline bitartrate ampoules for infusion supplied by PARCOTIC with a labelled concentration of 1 mg mL^{-1}. The standard addition method was employed, in which a 1 mM adrenaline standard solution was added sequentially. For sample preparation, 200 µL of the real sample (with unknown concentration) was diluted in 100 mL of a buffer electrolyte solution. Based on the peak oxidation current of adrenaline, a calibration curve was generated to enable the quantification of adrenaline in real samples. Using the calibration equation, I = 26.64 + 1.89 c_A and the measured peak current of 37.6 nA, the concentration of adrenaline in the solution was calculated to be 5.8 µM, corresponding to 0.967 mg mL^{-1}, assuming a molar mass of adrenaline bitartrate (M = 333.29 g mol^{-1}). In addition, the recoveries and relative standard deviations (RSD) for the cobalt(II) complex in the pharmaceutical sample ranged from 89.55 to 102.92 % and from 0.30 to 0.70 %, respectively. A detailed summary of these results can be found in Table 3 and the corresponding differential pulse voltammograms (DPV) are shown in Figure 10.

The newly developed cobalt(II) complex-based sensor showed satisfactory analytical performance, demonstrating its suitability for the quantitative determination of adrenaline in pharmaceutical formulations.

The detection limit (LOD) was calculated using the following formula: LOD = 3σ/S, where σ is the standard deviation of the blank signal (n = 10) and S is the slope of the calibration curve. The standard deviation (σ) used for the calculation was 0.0082 µA, and the slope of the calibration curve was 26.92 nA µM^{-1}. This calculation resulted in an LOD of 0.09 µM, as shown in Table 4.
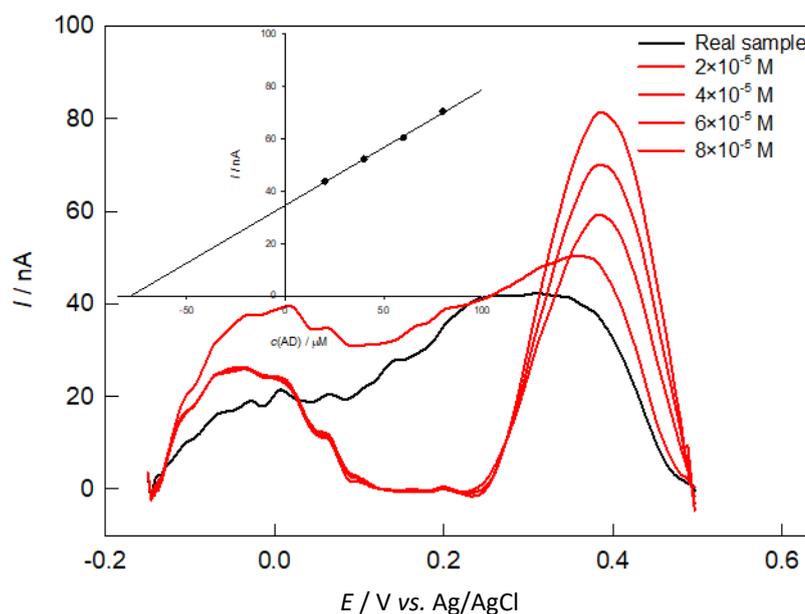
Figure 10. *DPVs of a real adrenaline sample (corrected for the Co(II) complex current), recorded at the Co(II)-complex-modified GCE and the corresponding calibration curve*

Table 3. *The application of GCE modified with cobalt(II) complex for the determination of adrenaline (n = 3) in pharmaceutical samples*

Sample no.	Real sample volume, µL	Nominal c_{AD} / µM	Peak current, nA	Found c_{AD} / µM	Recovery, %	RSD, %
1		-	37.6	5.8	-	-
2		25.0	76.5	26.4	102.92	0.30
3	200	45.5	114.2	46.3	101.36	0.31
4		66.0	142.9	61.4	92.68	0.67
5		86.5	173.1	77.4	89.55	0.70

Table 4. *A comparison of the analytical performance between the previously reported methods and the proposed sensor for AD detection*

Modified electrode materials	Detection technique	Linear range, µM	Sensitivity, nA µM^{-1}	LOD, µM	Ref.
BDDFE	SWV	0.7 to 60	29	0.21	[3]
CQDs/CPE	CA	0.02 to 0.8 and 0.8 to 20	-	0.006	[43]
La$_2$CuO$_4$/CPE	DPV	16 to 380	5	19.0	[42]
AgNPs-PCA-Au electrode	CA	10^2 to 10^5	-	0.0005	[17]
NOGG/GP	DPV	0.1 to 5	25.6	0.05	[44]
		5 to 130	30.0		
PGCE	SWV	10.3 to 102.7	16825.5	2.86	[45]
Naf-TMS/GCE	DPV	1 to 20	570	0.52	[46]
Naf-TMS/[Ru(bpy)$_3$]$^{2+}$/GCE		1 to 100	510	0.58	
Naf-TMS/[Ru(phen)$_3$]$^{2+}$/GCE		1 to 100	450	0.68	
GCE/cobalt(II) complex	DPV	0.1 – 2.0	26.92	0.09	This work

Abbreviations: AgNPs - silver nanoparticles, BDDFE - boron-doped diamond film electrode, CA - chronoamperometry, CPE - carbon paste electrode, CQDs - carbon quantum dots, CV - cyclic voltammetry, DPV - differential pulse voltammetry, GCE - glassy carbon electrode, GP - graphite paste electrode, Naf-TMS - Nafion–trimethylsilyl, NOGG - Nd$_2$O$_3$ nanoparticle grafted graphene nanocomposite, PCA-Au - electrode; penicillamine self-assembled gold electrode, PGCE - poly(crystal violet) modified glassy carbon electrode, SWV - square-wave voltammetry.

As shown in Table 4, GCE modified with the Co(II) complex has a low detection limit (0.09 µM) and satisfactory sensitivity (26.92 nA µM^{-1}), making it one of the most effective electrochemical sensors for adrenaline detection. While some reported sensors achieve either a lower LOD or a wider linear range, the proposed sensor offers a favourable balance of analytical parameters, making it a competitive candidate for practical applications.

Conclusion

In this work, the electroanalytical application of the cobalt(II) coordination compound $\{[Co(1,2\text{-bpe})_2(H_2O)_2](6\text{-NH}_2\text{nic})(NO_3)\times 4H_2O\}_n$ for the determination of adrenaline was investigated. Using a modified glassy carbon electrode (GCE) and applying cyclic voltammetry and electro-chemical impedance spectroscopy (EIS), the ability of this complex to facilitate the oxidation of adrenaline was determined, making it suitable for its detection in the pharmaceutical sample. The modified electrode showed significant sensitivity and selectivity towards adrenaline, with improved electroanalytical properties compared to the unmodified electrode.

The spectrophotometric analysis, which confirmed the formation of a stable complex between adrenaline and Co(II), contributed to the understanding of the interaction between the cobalt(II) complex and adrenaline. The linear relationship between the peak current and the adrenaline concentration resulting from the calibration curve allowed the accurate determination of the adrenaline concentration in a real sample. The results of this study suggest that the cobalt coordination compound, Co(II) has great potential for the electrochemical determination of adrenaline due to its favourable complexation and selectivity properties and ease of use. This approach could be further developed to create commercial sensors for the rapid and efficient detection of adrenaline in biological and pharmaceutical samples, which would enable wider application in clinical diagnostics and analytical laboratories.

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