Full Paper

The Mathematical Description for Insubosin Electrochemical Detection, Assisted by coo(oh) – poly(3,4-Ethylendioxythiophene) Composite

Volodymyr V. Tkach,[1,2] Yana G. Ivanushko,[1] Svitlana M. Lukanova,[1] Lyudmyla V. Romaniv,[1] Sílvio C. de Oliveira[2] and Petro I. Yagodynets´

[1]*Chernivtsi National University, 58012, Kotsyubyns'ky Str., 2, Chernivtsi, Ukraine*

[2]*Universidade Federal de Mato Grosso do Sul, Av. Sen. Felinto. Müller, 1555, C/P. 549, 79074-460, Campo Grande, MS, Brazil*

[3]*Bukovyna State Medical University, 58000, Teatral´na Sq., 2, Chernivtsi, Ukraine*

*Corresponding Author, Tel.: +380506400359; Fax: +5521991809675

E-Mail: nightwatcher2401@gmail.com

Abstract- The possibility of Insubosin electrochemical determination, assisted by CoO(OH) – Poly(3,4-ethylendioxythiophene) hybrid material has been evaluated. The correspondent mathematical model has been developed and analyzed by means of linear stability theory and bifurcation analysis. It was shown that the hybrid material may be applied as an efficient electrode modifier in the detection of Insubosin as sodium salt in neutral and lightly alkaline media. The electrochemical response has to be clear and easy to interpret. The possibility of the oscillatory and monotonic instabilities has also been verified.

1. INTRODUCTION

The use of chemically modified electrodes (CME) is a very important step in electroanalytical chemistry [1-4]. Compared to the bare electrodes, they have some advantages, like:

- Rapidity;
- Low cost;
- Precisity;
- Exactity;
- Flexibility;
- Versatility in use;
- Affinity between the electrode modifier and the analyte.

On the other hand, insubosin [5] is a recently isolated alkaloid group from Streptomyces sp. IFM 11440. It contains hydroxymethyl group in the position 2 of the ring and hydroxyl groups in the positions 4, 5 and both (Fig. 1)
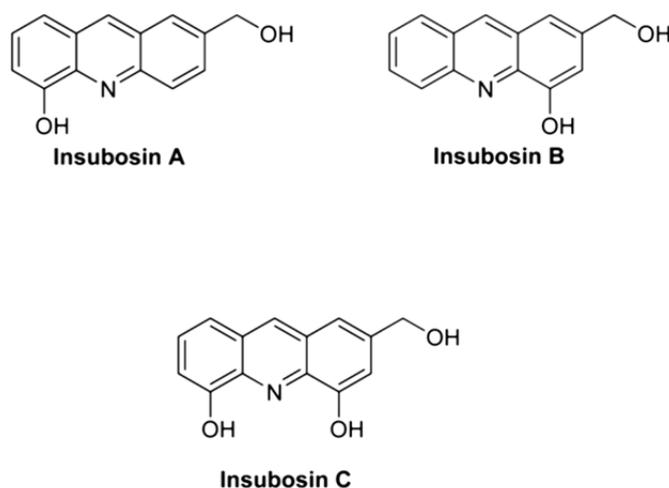

Insubosin A   **Insubosin B**

Insubosin C

Fig. 1. Insubosin alkaloid group

Insubosin B bearing a hydroxy group at the 4 position showed potent Ngn2 promoter activity, which was dose-dependent. Moreover, compound demonstrated more activity than baicalin, while insubosins with the hydroxyl in the position 5, did not show significant activity [5, 6]. Nevertheless, their biological activity in other aspects may not be discarded. In general, acridinic compounds have exhibited bioactivities such as anti-inflammatory [7,8], anticancer [9], antimicrobial [10], antitubercular [11-12], antiparasitic,[13-15] and other. Nevertheless, their activity is dose-related, and acridinic ring may possess toxic properties including mutagenic and teratogenic effects [16-18]. So, the development of an efficient and rapid insubosin group determination method is really actual task.

For now, no electrochemical methods for insubosin analytical determination have been applied, and there is only one work, related to its detection in fungi [5]. However, its chemical composition may lead to the hypothesis that cobalt (III) oxyhydroxide [19-20] and its composite with a Poly(3,4-ethylendioxythiophene), in which CoO(OH) could be used as an electrode mediator for its determination.

Nonetheless, the development of new electroanalytical systems may confront the problems like:

- the indecision in the analyte oxidation mechanism and in the modifier function;
- the compatibility of the modifier with the pharmaceutical tissue or biological object (some modifiers, used *in vitro* may be non-compatible with *in vivo* sensing, or require pre-treatment);
- The presence of electrochemical instabilities, accompanying both electrochemical synthesis of cobalt(III) oxyhydroxide [21-22], and electrochemical oxidation and electrooxidative polymerization of conjugated organic molecules [23-25].

The mentioned problems may only be solved by means of an analysis of a mathematical model, capable to describe adequately the electroanalytical system. By modeling it is also capable compare the behavior of this system with that for the similar ones without any experimental essay.

So, the goal of this work is the mechanistic theoretic analysis of the possibility of Insubosin electrochemical quantification, assisted by the CoO(OH)–Poly(3,4-ethylendioxythiophene) composite. In order to achieve it, we realize the specific goals:

- suggestion of the mechanism of the electroanalytical reaction consequence, leading to the appearance of analytical signal;
- development of the balance equation mathematical model, correspondent to the electroanalytical system;
- analysis and interpretation of the model in terms of the electroanalytical use of the system;
- the seek for the possibility of electrochemical instabilities and for the factor, causing them;
- the comparison of the mentioned system´s behavior with the similar ones [26-28].

2. SYSTEM AND ITS MODELING

As mentioned in the previous section, in the electroanalytical process, the roles of the inorganic and organic parts of the composite are distributed according to the Fig. 2:
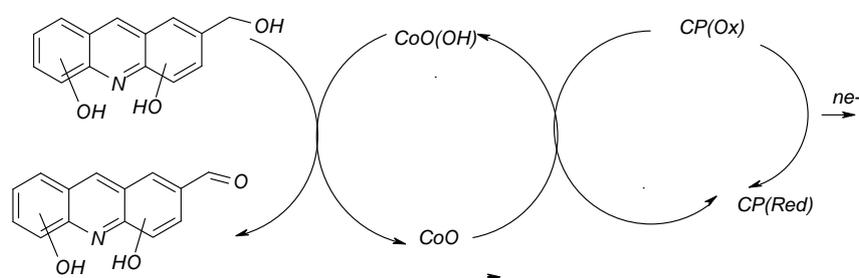

Fig. 2. The scheme of electron transference for Insubosin electrochemical detection, assisted by the CoO(OH) – Poly(3,4-ethylendioxythiophene) composite

The electrooxidation of the proper acridinic ring, due to the presence of the acceptor pyridinic nitrogen atom, is given in relatively high potentials. Nevetheless, if the redox pair $CoO(OH) - CoO_2$ is used, this scenario may be also possible.

So, taking this into account, we describe the behavior of this system using a trivariant system with the variables like:

c – the Insubosin concentration in the pre-surface layer;

θ – the CoO surface coverage degree;

μ – the coverage degree of the Poly(3,4-ethylendioxythiophene) in its reduced form.

To simplify the modeling, we suppose that the reactor is intensively stirred, so we can neglect the convection flow. Also we assume that the background electrolyte is in excess, so we can neglect the migration flow. The diffusion layer is supposed to be of a constant thickness, equal to δ, and the concentration profile in it is supposed to be linear.

In the simplest case, in which neither CoO(OH), nor polymer enter in the side reactions, the system will be described by the classical trivariant equation set, exposed as:

$$\begin{cases} \frac{dc}{dt} = \frac{2}{\delta}\left(\frac{\Delta}{\delta}(c_0 - c) - r_1\right) \\ \frac{d\theta}{dt} = \frac{1}{G}(r_1 - r_2) \\ \frac{d\mu}{dt} = \frac{1}{M}(r_2 - r_3) \end{cases} \tag{1}$$

In which Δ is the diffusion coefficient, c_0 is Insubosin bulk concentration, G and M are CoO and polymer maximal concentration and the parameters r are correspondent reaction rates, defined as:

$$r_1 = k_1 c (1 - \theta)^2 \quad r_2 = k_2 \theta (1 - \mu) \quad r_3 = k_3 \mu \exp\frac{nF\varphi_0}{RT} \tag{2-4}$$

In which the parameters k are correspondent reaction rate constants, n is the number of electrons transferred, F is the Faraday number, φ_0 is the DEL potential slope in the double, related to the zero-charge potential, R is the universal gas constant and T is the absolute temperature.

3. RESULTS AND DISCUSSION

In order to investigate the behavior of the system with the Insubosin electrochemical determination, assisted by CoO(OH)–Poly(3,4-ethylendioxythiophene) composite, we analyze the equation set (1) by means of the linear stability theory. The steady-state Jacobian matrix elements may be described as:

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \tag{5}$$

In which:

$$a_{11} = \frac{2}{\delta}\left(-\frac{\varLambda}{\delta} - k_1(1-\theta)^2\right) \tag{6}$$

$$a_{12} = \frac{2}{\delta}\left(2k_1 c(1-\theta)\ \right) \tag{7}$$

$$a_{13} = 0 \tag{8}$$

$$a_{21} = \frac{1}{G}\left(k_1(1-\theta)^2\right) \tag{9}$$

$$a_{22} = \frac{1}{G}\left(-2k_1 c(1-\theta)\ \ -k_2(1-\mu)\right) \tag{10}$$

$$a_{23} = \frac{1}{G}\left(k_2\theta\right) \tag{11}$$

$$a_{31} = 0 \tag{12}$$

$$a_{32} = \frac{1}{M}\left(k_2(1-\mu)\right) \tag{13}$$

$$a_{33} = \frac{1}{M}\left(-k_2\theta - k_3 \exp\frac{nF\varphi_0}{RT} - jk_3\mu \exp\frac{nF\varphi_0}{RT}\right) \tag{14}$$

Similarly to the more general case of [30], and in similar cases of [31-35] *the oscillatory behavior* for this system is possible and it will be caused uniquely by influences of Poly(3,4-ethylendioxythiophene) reduced form electrochemical oxidation on DEL capacitances, described by the positivity of main-diagonal element $-jk_3\mu \exp\frac{nF\varphi_0}{RT}$ (positive main-diagonal elements describe the positive callback). The oscillations are expected to be frequent and of little amplitude, and their frequency will depend on the nature of the solution and of the polymer (type of the monomer and its doping degree).

In order to analyze the *steady-state stability,* we apply the Routh-Hurwitz criterion to the equation set (1). In order to simplify the analysis, avoiding cumbersome expressions, we introduce new variables, so the matrix determinant will be described as:

$$\frac{2}{\delta GM}\begin{vmatrix} -\kappa - \varXi & \varLambda & 0 \\ \varXi & -\varLambda - \varSigma & \varOmega \\ 0 & \varSigma & -\varOmega - \varGamma \end{vmatrix} \tag{15}$$

Opening the brackets, and applying the condition of Det J<0, we obtain the steady-state stability requirement expressed as:

$$-\kappa(\varLambda\varOmega + \varLambda\varGamma + \varSigma\varGamma) - \varXi\varSigma\varGamma < 0 \tag{16}$$

And it is warranted to be satisfied in the case of the positivity of $\varGamma$, describing the fragility of DEL influences of the electrochemical process. In this case, the left side of the expression (16) tends to be more negative, satisfying the inequation. The process is, mostly, diffusion-controlled, but, taking into account that the reaction between CoO and the polymer may be slow, the kinetically controlled system is very probable. Even though, the linearity of the dependence between the electrochemical parameter and concentration is easy to maintain.

The *monotonic instability* in this system is possible, being caused by the equality between the stabilizing influences and the destabilizing ones of the electrochemical process influences on DEL. It is correspondent to the detection limit and its condition may be described as:

$$-\kappa(\Lambda\Omega + \Lambda\Gamma + \Sigma\Gamma) - \Xi\Sigma\Gamma = 0 \tag{17}$$

The simplest model, described here is applicable to the system only in the case of the solutions, in which CoO(OH) is stable. If CoO(OH) is dissolved, another interesting system surges. Despite of CoO(OH) dissolution, in some conditions, the system may be electroanalytically efficient, as Poly(3,4-ethylendioxythiophene) may assume the functions of active substance, making the electron transfer direct. This case will be evaluated in our next works.

4. CONCLUSION

From the theoretical investigation of the possibility of the Insubosin electrochemical detection, assisted by the CoO(OH)–Poly(3,4-ethylendioxythiophene) composite it is possible to conclude that:

- CoO(OH) and Poly(3,4-ethylendioxythiophene) may serve as an excellent modifier for Insubosin quantification. The CoO(OH) acts as an active substance, and the polymer as mediator. The stable steady-state is maintained easily. The system is electroanalytically efficient;
- Depending on the polymer nature and solution composition, the process may be diffusion- or reaction-controlled;
- The oscillatory behavior in this system is possible, being caused only by DEL influences of the electrochemical process. The amplitude is dependent on the polymer and colution composition.

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