Voltammetric and corrosion studies of the ionophoric antibiotic–salinomycin and its determination in a soil extract

Konrad Rudnicki, Sławomir Domagała, Barbara Burnat, Sławomira Skrzypek *

University of Lodz, Faculty of Chemistry, Department of Inorganic and Analytical Chemistry, Tamka 12, 91-403 Lodz, Poland

A B S T R A C T

Salinomycin monosodium salt (SLM) is a widely used ionophoric antibiotic with a broad spectrum of activity. In this paper, a study is reported on the first electrochemical investigation of SLM. The use of square wave voltammetry (SWV) in combination with a renewable silver amalgam film electrode (Hg(Ag)FE) is presented for the determination of SLM in a spiked soil extract. A reduction peak at -1.40 V vs. an Ag/AgCl/KCl reference electrode was obtained in Britton–Robinson (B–R) buffer (pH 7.0). The influences of conditioning potential and time, frequency, amplitude, step potential and equilibration time were studied. This electroanalytical procedure was used to determine SLM on an Hg(Ag)F electrode at a concentration range of 2.5×10^{-7}–2.5×10^{-6} mol L^{-1}. The precision and repeatability of the method were checked. The limit of detection and quantification were 7.8×10^{-8} mol L^{-1} and 2.5×10^{-7} mol L^{-1}, respectively. To understand the SLM electrode mechanism, the cyclic voltammetry (CV) technique was applied. Moreover, the effect of SLM on the corrosion properties of stainless steels used to produce metal bowls and feed troughs was studied using the potentiodynamic method.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Salinomycin monosodium salt (SLM), α-ethyl-6-[5-[2-(5-ethyltetrahydro-5-hydroxy-6-methyl-2*H*-pyran-2-yl)-15-hydroxy-2,10,12-trimethyl-1,6,8-trioxadispiro[4.1.5.3]pentadec13- en-9-yl]-2-hydroxy-1,3-dimethyl-4-oxoheptyl]tetrahydro-5-methyl-2*H*-pyran-2-acetic acid, is an important ionophoric antibiotic. SLM belongs to the group of veterinary, antibacterial and coccidiostat therapeutic drugs. Research on SLM has shown that the compound shows antimicrobial activity against Gram-positive bacteria, causing among others coccidiosis, a poultry disease [1]. Moreover, a group of scientists from the University of Cambridge discovered that SLM can kill cancer stem cells by slowing down their growth and metastasis in breast cancer in mice [2]. During the laboratory tests, SLM was a hundred times more efficient at killing breast cancer stem cells than Paclitaxel – the commonly used chemotherapy drug. Researchers have tested approximately 16,000 different substances that are able to kill tumour cells. Around 32 of these kill cancer cells, while normal cells are spared. Among these substances, SLM proved to be the most efficient and easiest to obtain in large quantities [3] (Fig. 1).

Based on the literature search, no electrochemical method has been reported for the determination of SLM. To the best of our knowledge, this is the first report on a voltammetric study of SLM on a renewable silver amalgam film electrode (Hg(Ag)FE). So far, SLM has been determined using techniques such as liquid chromatography (LC) with a tandem mass spectrometry detector (MS/MS) [4–9], high-performance liquid chromatography (HPLC) with UV/Vis [10] and a tandem mass spectrometry (MS/MS) detector [11], ultra-high performance liquid chromatography (UHPLC) with a tandem mass spectrometry (MS/MS) detector [12,13], high resolution/high accuracy Orbitrap® mass (HRMS) detector, mass spectrometry (MS) with inductively coupled plasma (ICP) [14] and laser induced fluorescence microscopy (LIFM) with nanoparticles [15]. Unfortunately, the above analytical methods have several disadvantages. Electrochemical techniques are characterized by lower apparatus cost, miniaturisation capability, suitability for real-time detection, short analysis time or less sensitivity to matrix effects in comparison to other methods [16]. Moreover, voltammetric techniques have high levels of reproducibility and repeatability for measurements, as well as a high degree of sensitivity.

Until recently, mercury electrodes have been used in voltammetric studies of the electro-reduction process. Development of new environmentally-friendly electrode materials that could replace mercury due to its toxicity is one of the modern trends of green chemistry [17]. A good example of an innovative renewable-film electrode surface is a renewable silver amalgam film electrode (Hg(Ag)FE) [18]. Using silver as a primer for the silver amalgam film is proven to be the ideal solution.

* Corresponding author.
E-mail addresses: rudnik503@gmail.com (K. Rudnicki), domagala@chemia.uni.lodz.pl (S. Domagała), burnat@chemia.uni.lodz.pl (B. Burnat), skrzypek@chemia.uni.lodz.pl (S. Skrzypek).
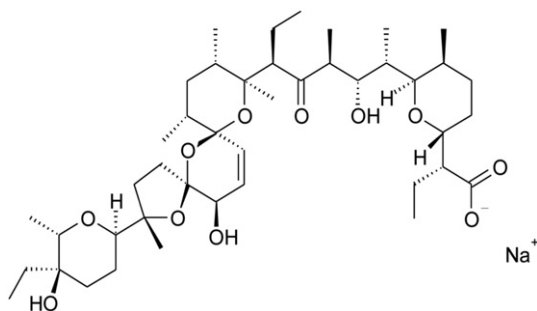
Fig. 1. The structure of SLM monosodium salt.

During the construction of an Hg(Ag)F electrode, it appeared that silver offers very good wettability by mercury, while poorly dissolving in it [19–22]. This electrode successfully determined trace amounts of many elements, drugs, pesticides, vitamins and many others [23–38].

Additionally, the corrosivity of SLM towards steel was determined in the paper. Predominantly, metallic corrosion occurs via electrochemical reactions at the interface between the metal and the electrolyte solution. During electrochemical measurements, a metal sample is applied to model the metal in a corroding system [39]. Literature reports show that some organic compounds have a significant effect on the corrosion of metals [40–42]. Metal bowls, feed troughs and also agricultural tools used in farms are the most vulnerable to corrosion through contact with veterinary drugs, as well as their residues and metabolites. Some constituents in slurry and farmyard manure (urea, uric acid, ammonia, ammonium salts, and naturally excreted chloride) are also corrosive towards steel structures and machinery that are poorly protected and maintained. Therefore, we decided to study the corrosion effect of SLM on AISI Type 304 stainless steel used as a construction material in farming.

The aim of the study was to develop a method to determine SLM at Hg(Ag)FE and the procedure for its SWV determination in a spiked natural soil extract. Furthermore, cyclic voltammetry (CV) was applied to understand the mechanism of the SLM cathodic reduction process. In addition, the effect of the antibiotic on the corrosion properties of stainless steel used to produce metal bowls, feed troughs and agricultural tools was studied.

2. Materials and methods

2.1. Apparatus

The voltammetric measurements (SWV and CV) were performed on an AUTOLAB–PGSTAT302N potentiostat–galvanostat (Metrohm Autolab B.V., Switzerland–The Netherlands) controlled by NOVA 1.11.1 software in combination with an M164D electrode stand (MTM Anko Instruments, Cracow, Poland). Measurements were carried out in the traditional three-electrode system containing an Hg(Ag)FE as a working electrode (surface of 0.08 cm^2), a silver/silver chloride electrode (Ag/AgCl, 3 M KCl) as a reference electrode and a platinum wire as a counter electrode.

The pH measurements were performed using a type HI 221 pH-metre (Hanna Instruments, Poland) with a type EPS-1 glass membrane electrode (Elmetron, Poland).

Corrosion measurements were carried out using an AUTOLAB PGSTAT 30 potentiostat–galvanostat (EcoChemie Autolab B.V., Utrecht, The Netherlands) controlled by GPES 4.9 software. In corrosion tests, a conventional three–electrode cell assembly was used. AISI Type 304 stainless steel was used as a working electrode (an exposed area of 0.64 cm^2), a saturated calomel electrode (SCE, Eurosensor, Gliwice, Poland) was applied as a reference electrode, and platinum foil (99.9%, Mennica Polska S.A., Warsaw, Poland) was used as a counter electrode.

A PHENOM G2 Purescanning electron microscope (PHENOM WORLD) was used for the characterization of corrosion damage.

2.2. Reagents and solutions

SLM (CAS no. 55721–31–8) was purchased from Sigma-Aldrich (Poland). Fresh stock solution of SLM (1.0×10^{-3} mol L^{-1}) was prepared every 10 days by dissolving 7.7 mg of the antibiotic into 10 mL of ethanol. The solution was placed in an ultrasonic bath for 10 min to dissolve the solid sample. As a supporting electrolyte Britton–Robinson (B-R) buffers (pH 2.0–9.0) were used. To obtain buffer solutions with different pH values, a solution of B-R matrix (0.04 mol L^{-1}: $H_3BO_3 + H_3PO_4 + CH_3COOH$ mixture) was titrated with 0.20 M NaOH. All chemicals used were of analytical reagent grade (Avantor Performance Materials Poland S.A; Sigma-Aldrich, Poland; Chempur, Poland). Before the analysis was carried out, all solutions were prepared with triple distilled water and stored at 4 °C in a fridge.

Sodium chloride (analytical reagent grade, POCH SA, Gliwice, Poland) was used as the corroding medium. Corrosion tests were carried out in a 3.5% solution of NaCl prepared in a water–ethanol mixture (1:1, v/v), both with and without the addition of SLM (1.0×10^{-3} mol L^{-1}). The solutions were used without further deoxygenation.

Argon (99.99%, ALPHAGAZ, Poland) was used as a neutral gas for the deoxygenation of solutions.

2.3. Measurement procedures

2.3.1. General voltammetric procedure

The solution for the supporting electrolyte contained 5 mL of the appropriate B–R buffer and 5 mL of triple distilled water. Each solution was purged with argon for 10 min while stirring. When the blank was recorded, the required volumes of SLM solution were added by a micropipette to obtain the analytical signal. If reagents were added, the purge process was repeated for a further 30 s with stirring.

The Hg(Ag)FE surface required special chemical activation and pretreatment before use [30–32]. Chemical activation of the electrode in 2% HNO$_3$ for about 5 min was applied, if a loss of sensor sensitivity was observed. Furthermore, the procedure for refreshing the Hg(Ag)FE surface was performed before each measurement [30]. After the formation of a new layer, a conditioning step was performed by the application of −1.90 V potential for 60 s. During the resting period ($t_{eq} = 40$ s), a negative potential was applied (−1.90 V), and after this time the voltammograms were recorded. The initial quantitative studies were performed in the potential range from 0 to −1.80 V, later the potential window was narrowed, because in the studied range the only one signal was observed. The reported signals were measured after subtracting those for the blank solution and using the Savitzky-Golay procedure for smoothing (SG Smooth analysis tool, level 3) available in NOVA 1.11.1 software.

2.3.2. Corrosion procedures

Before corrosion measurements, the surfaces of each AISI 304 stainless steel sample (disc with a diameter of 14 mm and a thickness of 6 mm) were ground on SiC abrasive paper (320, 500, and 1000 grits), cleaned in water in an ultrasonic bath for 10 min, rinsed with ethanol and dried with argon. The corrosion resistance of AISI 304 stainless steel in SLM-containing sodium chloride solutions was studied via the potentiodynamic method. Firstly, the corrosion potential (E_{cor}) in an open circuit (OCP) was measured over 2000 s. Then, the measurement of the potentiodynamic characteristic was performed in a scanning potential range from 0.2 V below E_{cor} up to +0.5 V, with a scan rate of 1 mV s^{-1}. Next, the surfaces of samples were examined using a scanning electron microscope for the characterization of corrosion damage. Four samples were used for every corrosion test. The corrosion results presented in this paper are averaged values with standard deviations.