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Tetralactam-modified gold electrodes for amperometric detection of acrylic acid

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The presence of toxic acrylamide in a wide range of food products such as potato crisps, French fries or bread has been confirmed by Swedish scientists from Stockholm University. The neurotoxicity and possible carcinogenicity of this compound and its metabolites compel us to control them by quantitative and qualitative assays. Exposing acrylamide to pH extremes results in its hydrolysis to acrylic acid or its salt. In this work, we present the use of gold electrodes coated with self-assembled monolayers (SAMs) containing tetralactam molecules and its precursor as active elements for voltammetric detection of acrylic acid in water solution. The host molecules have been immobilised on the electrode surface by covalent Au—S bond or by embedment method into the thiol layer via hydrophobic and van der Waals interactions. Interactions with analytes were confirmed by Osteryoung square-wave voltammetry.

Keywords: acrylic acid; tetralactam; OSWV; gold electrodes

Introduction

Acrylamide is a well-known neurotoxin and potential carcinogen (*1*, *2*). High levels of this compound have been found in potato chips, French fries and several other common foods (*3–5*). The first such report was announced by scientists from Stockholm University in 2002 (*3*). Acrylamide forms in the reaction between reducing sugars such as glucose and amino acid asparagine. The Millard reaction mechanism has been proposed to account for its formation in high-starch foods during cooking at high temperature (*6–8*). Investigation has shown that high temperature and long heat treatment result in higher acrylamide content (*6*). Among analytical methods used to determine acrylamide levels, expensive and time-consuming chromatographic techniques such as GC–MS (*9*), GC–MS–MS (*10*), HPLC–MS (*11*) and LC-MS–MS (*5*) predominate. Preparation of samples from food involves extraction using water or methanol, and the clean-up step typically consists of a combination of several solid-phase extractions. GC–MS often needs the additionally laborious bromination step to form more volatile acrylamide derivative and increase the selectivity of determination. Only a few examples of using different techniques for the detection of this toxic compound exist. Stobiecka et al. (*12*) introduced a voltammetric sensor based on the reaction of haemoglobin with acrylamide. This reaction leads to haemoglobin–acrylamide adducts formation that alters the electroactivity of haemoglobin. This biosensor showed good selectivity and sensitivity.

Exposing acrylamide to pH extremes results in its hydrolysis to acrylic acid or its salt. The most frequently used methods of acrylic acid determination also include GC (*13*) and HPLC (*14*). Ignatov et al. prepared a biosensor in which respiratory activity of microbial cells was used for the detection of acrylamide and acrylic acid (*15*). Kleefish et al. (*16*) reported a sensor in which acrylamide and acrylic acid were detected at a gas–solid interface using an 'electronic nose'-type quartz crystal microbalance sensor covered with a tetralactam active layer. This system had not previously been tested at water–organic interface.

Tetralactams belong to a wide group of neutral compounds that are able to complex anions by hydrogen bond formation (*17*, *18*). These macrocycles have been used recently as the macrocyclic host for the detection of carbonyl compounds. Hunter showed that such a macrocycle can complex *p*-benzoquinone and the recognition process can be achieved via a combination of $\pi-\pi$ interaction and four hydrogen bond formations to the quinone oxygens. This phenomenon was confirmed by a ^{1}H NMR experiment performed in $CDCl_3$ (*19*). A similar experiment performed in CD_2Cl_2 and mixture of CD_2Cl_2/CD_3OD at a 4:1 ratio showed interaction of these compounds with Br^-, Cl^-, weaker with NO_3^- and AcO^- (*20*). Tetralactam has been used in an electronic nose sensor to create a sensitive and selective active layer on the gold surface of quartz crystal electrodes and detect apple ester, 2-hexenal, S-limonene and 2-heptanon (*21*, *22*).

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Hydrogen bonds formation and π–π interaction were responsible for the formation of catenate and rotaxanes. Their synthesis was based on the action of supramolecular nucleophile that is formed from the molecular recognition of an anionic stopper by a tetralactam wheel (*23–25*).

Similar macrocycles containing pyridine fragments showed binding affinities for a diamide guest ($Et_2NC(O)(CH_2)_4C(O)NEt_2$). These interactions were investigated also in $CDCl_3$ by a ^1H NMR titration experiment (*26*).

In this paper, we present the use of gold electrodes coated with SAMs containing tetralactam macrocycle and its acyclic derivative (Figure 1) as active elements for voltammetric detection of acrylic acid in water solution. The host molecules have been immobilised on an electrode surface by covalent Au—S bond or by embedment method into the thiol layer via hydrophobic and van der Waals interactions. Influence of modification type on electrode sensitivity has been investigated.

Experimental

Reagents and materials

1-Dodecanethiol (DDT), $[Ru(NH_3)_6]Cl_3$ and acrylic acid were purchased from Aldrich Chemie (Steinheim, Germany). Potassium nitrate was purchased from POCh (Gliwice, Poland). Aqueous solutions were prepared with deionised water (18.2 MΩ cm resistivity) obtained with a Simplicity® 185 Water System (Millipore, Molsheim, France).

Synthesis of receptors

Receptors 1–3 have been synthesised in the Department of Chemistry, University of Leuven (Figure 2). Dodecyloxyisophthaloyl dichloride **1** (*27*), bisamine **2** (*23*), monoBoc derivative **6** (*28*) and benzyloxyisophthaloyl dichloride **9** (*29*) were obtained according to the literature procedures. All other reagents were obtained commercially and used as received. NMR spectra were recorded on a Bruker Avance 300 or 400.

*5-Dodecyloxyisophthaloyl bis(diamine) **3** (receptor 3)*

Diamine **2** (21.0 g; 65.2 mmol) was dissolved in CH_2Cl_2 (100 mL) and triethylamine (3.2 mL) was added. 5-Dodecyloxyisophthaloyl dichloride (4.50 g; 11.6 mmol) **1** was similarly dissolved in CH_2Cl_2 (100 mL) and added dropwise to the diamine solution for 2 h with stirring under argon. The solvent was evaporated under reduced pressure and the dissolved residue was purified by column chromatography on silica with 7:1 CH_2Cl_2/ethyl acetate as the eluent yielding **3** (2.9 g; 26.3%). ^1H NMR (δ, $CDCl_3$, 400 MHz) 7.97 (s, 1H), 7.57 (s, 2H), 7.43 (s, 2H), 7.00 (s, 4H), 6.85 (s, 4H), 4.07 (t, 2H), 3.45 (s, br, 4H), 2.19

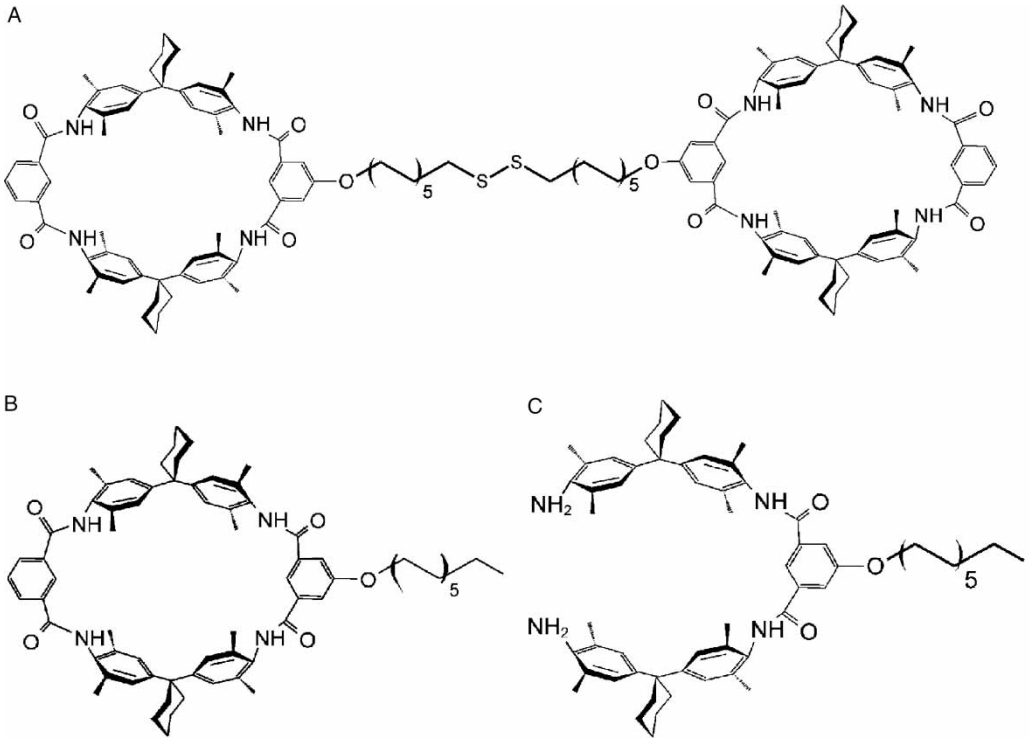


Figure 1. Structural formulae of ionophores used for the modification of electrodes with (A) covalent and (B and C) embedment methods.

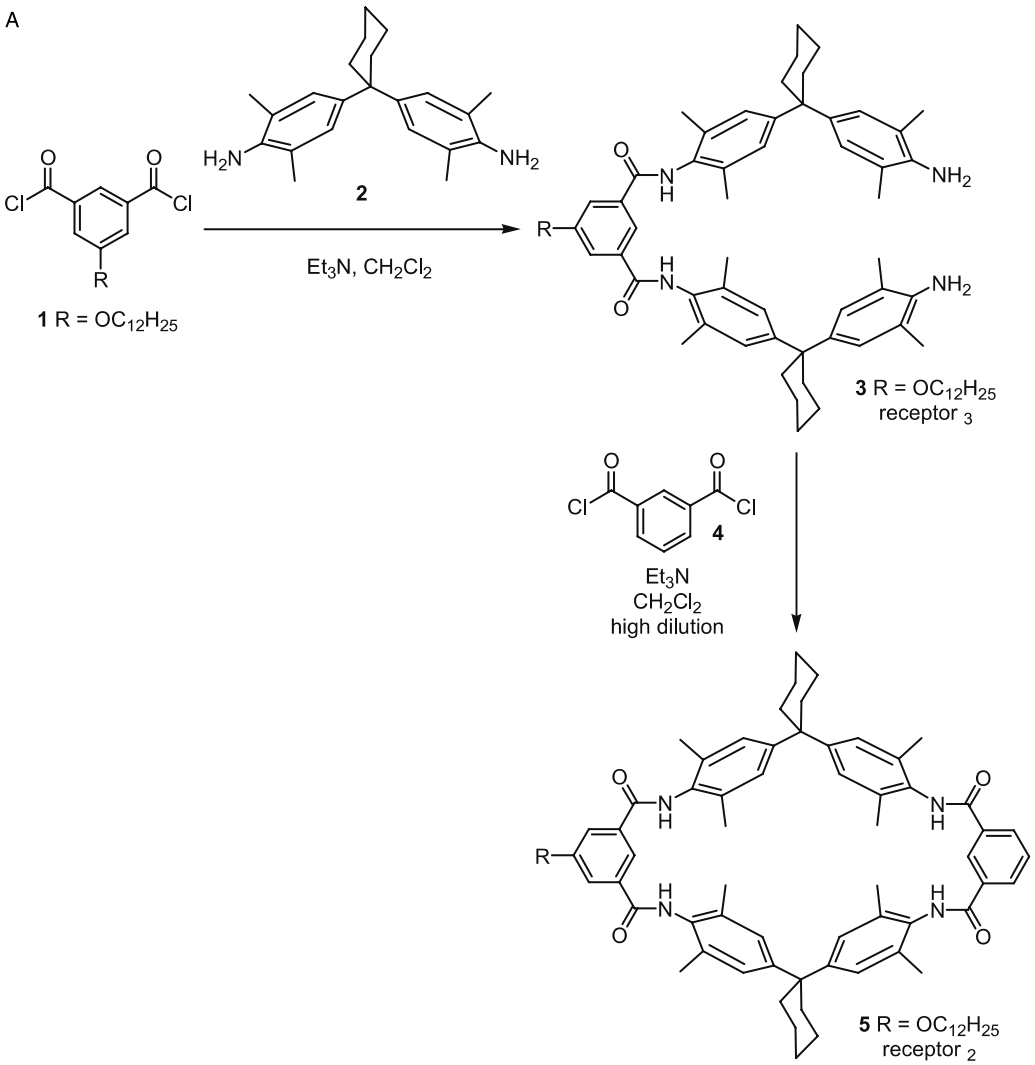
(m, br, 16H), 2.14 (s, 12H), 1.81 (m, 2H), 1.54–1.47 (m, 16H), 1.25–1.27 (m, 20H), 0.87 (t, 3H). ESI-MS (*m*/*z*) 960 MH^+.

*Macrocyclic tetralactam **5** (receptor 2)*

Diamine **3** (0.91 g; 0.95 mmol) and Et_3N (0.29 g; 2.8 mmol) were dissolved in CH_2Cl_2 (20 mL). Isophthaloyl dichloride **4** (0.19 g; 0.95 mmol) was dissolved in a separate volume of CH_2Cl_2 (20 mL). Both solutions were slowly added with an infusion pump for 4 h to a stirred volume of CH_2Cl_2 (1.2 L) at room temperature. After complete addition, stirring was continued for 10 h at room temperature, after which the solvent was evaporated under reduced pressure. The residue was subjected to column chromatography on SiO_2 with 4:1 CH_2Cl_2/ethyl acetate as the eluent yielding **5** as a white solid in 16% yield. ^1H NMR (δ, $CDCl_3/CH_3OD$ 19:1, 300 MHz) 8.31 (m, br, 1H), 8.16–8.13 (m, br, 2H), 7.85 (s, br, 1H), 7.66–7.65 (m, br, 3H), 6.99 (s, 8H), 4.09 (t, 2H), 2.45 (m, br, 4H), 2.34 (m, br, 4H), 2.27 (m, br, 16H), 2.17 (s, 12H), 1.82 (m, 2H), 1.65 (m, br, 4H), 1.52 (m, br, 4H), 1.27–2.25 (m, br, 20H), 0.88 (t, 3H). ESI-MS (*m*/*z*) 1089 MH^+.

*Boc-protected bisamide **7***

Mono-boc-protected derivative **6** (2.1 g; 5.0 mmol) and Et_3N (0.50 g; 5.0 mmol) were dissolved in CH_2Cl_2 (60 mL) and added dropwise for 30 min to a stirred solution of isophthaloyl dichloride **4** (0.50 g; 2.5 mmol) in CH_2Cl_2 (100 mL) at room temperature. After complete addition, the solution was stirred for another 2 h and the solvent was evaporated under reduced pressure. The target bisamide **7** was obtained after column chromatography on SiO_2 with 4:1 CH_2Cl_2/ethyl acetate as the eluent as a white solid in 76% yield. ^1H NMR (δ, $CDCl_3$, 300 MHz) 8.52 (s, 1H), 8.22 (m, br, 2H), 7.74 (m, br, 2H), 6.69 (s, 4H), 6.96 (s, 4H), 6.81 (s, br, 1H), 5.97 (s, br, 2H), 2.19 (m, br, 16H),



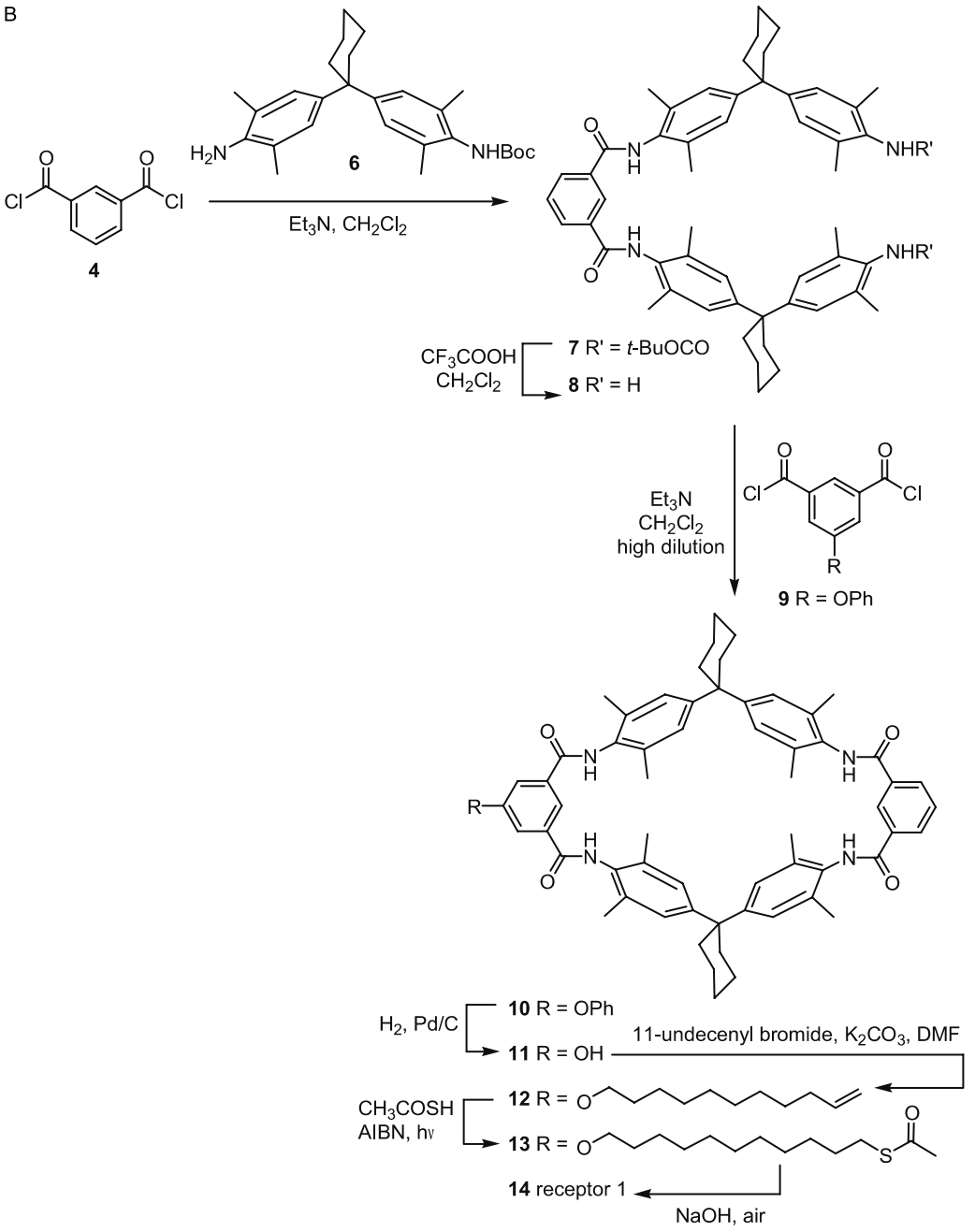


Figure 2. Synthetic route to obtain (A) receptors 2 and 3 and (B) receptor 1.

2.06 (s, 12H), 1.55–1.39 (m, br, 16H), 1.39 (s, 18H). ESI-MS (*m*/*z*) 975 MH^+.

*Bisamine **8***

To bisamide **7** (1.95 g; 2.0 mmol), CH_2Cl_2 (5 mL) and trifluoroacetic acid (5 mL) were added and the resulting mixture was stirred for 1 h at room temperature. The mixture was poured into an aqueous saturated $NaHCO_3$ solution (100 mL) and the resulting suspension was extracted with CH_2Cl_2 (3 × 70 mL). The combined organic layers were dried over $MgSO_4$ and the solvent was evaporated under reduced pressure, yielding bisamine **8** as a white solid in 83% yield. The spectral data were found to be identical to the published data (*23*).

*Benzyl-protected macrocyclic tetralactam **10***

Bisamine **8** (1.2 g; 1.6 mmol) and Et_3N (0.48 g; 4.8 mmol) were dissolved in CH_2Cl_2 (15 mL) and dicarbonyl

dichloride **9** (0.49 g; 1.6 mmol) was dissolved in another volume of CH_2Cl_2 (15 mL). Both solutions were added dropwise at room temperature to a stirred volume of CH_2Cl_2 (1.5 L) for 4 h. Stirring was continued for 10 h at room temperature. The solvent was evaporated under reduced pressure and the macrocyclic tetralactam **10** was obtained as a white solid after column chromatography on SiO_2 with 4:1 CH_2Cl_2/ethyl acetate as the eluent 21% yield. ^{1}H NMR (δ, $CDCl_3$, 300 MHz) 8.37 (s, 1H), 8.16 (d, 2H), 7.94 (s, 1H), 7.83–7.77 (m, 4H), 7.71 (s, 2H), 7.45–7.32 (m, 5H), 6.98 (s, 8H), 5.18 (s, 2H), 2.78 (s, 6H), 2.53 (s, 6H), 2.30–2.33 (m, 6H), 2.16 (s, 8H), 1.62–1.51 (m, 12H). ESI-MS (*m*/*z*) 1033.6 MNa^+.

*Undecenyloxy substituted macrocyclic tetralactam **12***

Benzyl-protected tetralactam **10** (100 mg; 0.099 mmol) was dissolved in a 1:1 mixture of $CHCl_3$ and ethanol (12 mL). Palladium on carbon (10%; 0.5 g) was added and the resulting suspension was shaken vigorously for 15 h under hydrogen atmosphere. The suspension was filtered over Celite and the solids were washed with ethanol (2 × 5 mL). The combined filtrates were evaporated under reduced pressure and the residue containing phenol **11** was dissolved in dimethylformamide (DMF) (10 mL). 11-Undecenyl bromide (46 mg; 0.20 mmol) and K_2CO_3 (28 mg; 0.20 mmol) were added and the resulting suspension was heated under continuous stirring at 80°C under argon atmosphere. After cooling to room temperature, the solvent was evaporated under reduced pressure and CH_2Cl_2 (10 mL) and water (10 mL) were added to the residue. After vigorous shaking, the organic layer was separated, dried over $MgSO_4$ and evaporated under reduced pressure. The title compound **12** was obtained as a white solid after column chromatography over SiO_2 with 4:1 CH_2Cl_2/ethyl acetate as the eluent in 72% yield. ^{1}H NMR (δ, $CDCl_3$/CH_3OD 19:1, 300 MHz) 8.36 (s, 1H), 8.14 (d, 2H), 7.86 (s, 1H), 7.66 (s, 2H), 7.64 (t, 1H), 6.99 (s, 8H), 5.82–5.71 (m, 1H), 5.01–4.90 (m, 2H), 4.09 (t, 2H), 2.33–2.03 (m, 32H), 1.81 (m, 4H), 1.65–1.52 (m, 12H), 1.30–1.32 (m, 12H). ESI-MS (*m*/*z*) 1072 MH^+.

*Thioacetate **13***

Undecenyloxy derivative **12** (80 mg; 0.075 mmol) was dissolved in a 1:1 mixture of CH_2Cl_2 and methanol (50 mL). Thioacetic acid (57 mg; 0.75 mmol) and azobisisobutyronitrile (AIBN) (2 mg) were added and the resulting solution was irradiated at room temperature with a UV lamp (375 nm, 50 W) under argon atmosphere for 12 h. The solvent was evaporated under reduced pressure and the residue was dissolved in a 9:1 mixture of CH_2Cl_2/methanol (approximately 0.5 mL). This solution was added dropwise to a stirred volume of diisopropyl ether (20 mL). The precipitate was filtered and washed with diisopropyl ether (2 × 5 mL) and dried in vacuum, yielding the title compound **13** in 86% yield. ^{1}H NMR (δ, $CDCl_3$, 300 MHz) 8.21 (tr, br, 1H), 8.14 (d, br, 2H), 8.13 (d, b, 2H), 7.72, s, br, 1H), 7.66 (m, b, 3H), 7.31 (s, 2H), 6.97 (s, 8H), 4.10 (t, br, 2H), 2.85 (t, 2H), 2.30–2.28 (m, br, + s, 11H), 2.18–2.16 (s, 16H), 1.86–1.82 (m, br, 4H), 1.67–1.64 (m, br, 8H), 1.56–1.53 (m, br, 14H), 1.30–1.26 (m, br, 12H). ESI-MS (*m*/*z*) 1150 MH^+.

*Receptor 1 (**14**)*

Thioacetate **13** (50 mg; 0.044 mmol) was dissolved in a 2:1 mixture of THF and methanol (5 mL). The resulting solution was placed in an airtight vial closed with a septum. Argon was bubbled through the solution for 15 min via a syringe to remove oxygen. An aqueous solution of NaOH (1 mL, 1 M) was added via a syringe while keeping the reaction mixture under argon. The mixture was left for 10 h at room temperature, after which diluted HCl was added (1.1 mL, 1 M) via a syringe. The solvents were evaporated under reduced pressure and the residue was treated with a 19:1 mixture of CH_2Cl_2 and methanol (approximately 2 mL) to dissolve the organic material. The resulting solution was filtered and the filtrate was added dropwise to a stirred volume of diethyl ether (10 mL) to precipitate **14** that was collected by filtration, washed with diethyl ether (2 × 2 mL) and obtained as a white solid in 45% yield. ^{1}H NMR (δ, $CDCl_3$/CH_3OH 19:1, 300 MHz) 8.30 (s, br, 2H), 8.16 (s, 8H), 8.09 (s, br 4H), 7.82 (t, br, 2H), 7.65 (tr + d, br, 6H), 6.98 (s, 16H), 4.08 (t, br, 4H), 2.68 (t, 4H), 2.34–2.32 (m, br, 16H), 2.17–2.15 (m, br + s, 40H), 1.86–1.82 (m, br, 8H), 1.66–1.63 (m, br, 16H), 1.49–1.28 (m, br, 44H). ESI-MS (*m*/*z*) 1129 $[(MNa)_2]^{2+}$.

Preparation of working electrodes

Gold disc electrodes (2 mm^2 area, Bioanalytical Systems (BAS) West Lafayette, IN, USA) were used for all experiments. Before modifications, the electrodes were cleaned mechanically by polishing with wet 0.3 and 0.05 μm alumina slurry (Alpha and Gamma Micropolish; Buehler, Lake Bluff, IL, USA) on a microcloth pad (BAS) and in a sonicator (30 s), then electrochemically by dipping in 0.5 M KOH solution and sweeping the potential between −400 and −1200 mV (versus a Ag/AgCl reference electrode) with a scan rate of 100 mV s^{-1} until cyclic voltammograms no longer changed. The stop potential was −400 mV.

Modification of electrodes

Covalent modification

Directly after cleaning, electrodes were soaked in 0.1 mM bis(tetralactam) disulphide solution (receptor 1) in ethanol/chloroform mixture (1/1 v/v) containing 1 mM

dodecanethiol at room temperature for 30 min. Then after washing with ethanol and water, the electrodes were stored in 0.01 M KNO_3 at room temperature until use.

Embedment modification

Directly after cleaning, the electrodes were soaked in 0.01 mM dodecanethiol solution in ethanol at room temperature for 30 min. After washing with ethanol, the electrodes were soaked in 1 mM solution of receptor 2 or 3 in ethanol for 12 h. Then after washing with ethanol and water, the electrodes were stored in 0.01 M KNO_3 at room temperature until use.

Before measuring, modified electrodes were stored in a solution containing 0.01 M KNO_3 (pH 5.0) for at least 1 day for conditioning.

Electrochemical measurement

All electrochemical measurements were performed with a potentiostat–galvanostat AutoLab (Eco Chemie, Utrecht, The Netherlands) with a three-electrode configuration. Potentials were measured versus the Ag/AgCl reference electrode obtained from BAS. The Ag/AgCl wire was placed in a glass tube filled with 3 M NaCl. The tube was closed with a vycor plug to protect the inner solution from direct contact with the sample solution. A platinum wire was used as the auxiliary electrode. Cyclic voltammetry (CV) was performed and potential was cycled from +50 to −500 mV for 1.0×10^{-4} M $[Ru(NH_3)_6]Cl_3$ with a scan rate of 500 mV s^{-1}. Osteryoung square-wave voltammetry (OSWV) was performed in the same potential range with a step potential of 5 mV, a square-wave frequency of 100 Hz and an amplitude of 25 mV. The dependence of the sensor responses on the concentration of analytes was expressed as the currents at the peak potential in OSWVs for $[Ru(NH_3)_6]^{3+}$ measured in a solution containing 0.01 M KNO_3. Electrochemical impedance spectroscopy (EIS) was performed within the frequency range of 0.1 Hz to 10 kHz at the formal potential of the redox couple $[Ru(NH_3)_6]^{2+/3+}$ (−0.2 V) with ac amplitude of 10 mV.

Results and discussion

Synthesis of receptors

An open chain bisamine **3** (receptor 3) was synthesised by the reaction of dodecyloxyisophthaloyl dichloride **1** (*27*) with a large excess of bisamine **2** (*23*) (Figure 2). Bisamine **3** was then cyclised to receptor 2 under high-dilution conditions by reaction with isophthaloyl dichloride (**4**). For the synthesis of receptor 1, we first started the preparation of bisamine **8** on the basis of the literature (*23*). However, it was found that large-scale preparation of the latter compound proceeded more conveniently via the protected precursor **7**, which was readily obtained by the reaction of equivalent amounts of isophthaloyl dichloride (**4**) and the monoprotected derivative **6** (*28*). After deprotection, the bisamine **8** was allowed to react with benzyloxyisophthaloyl dichloride **9** (*29*) under high-dilution conditions, yielding macrocyclic lactam **10**. Hydrogenolytic removal of the benzyl group followed by Williamson etherification afforded the alkenyl-substituted analogue **12** via intermediate phenol **11** – which was not isolated. After the radical addition of thioacetic acid, thioester **13** was isolated which, upon smooth basis hydrolysis in the presence of oxygen, gave rise to disulphide **14** or receptor 1.

Formation and characteristics of tetralactam SAMs

Our paper presents two methods of immobilisation of SAMs on gold electrode surfaces. The covalent method of modification involved one step in which DDT and bis(tetralactam) molecules (receptor 1; Figure 1) mixed in one solution were immobilised simultaneously on gold. Such a prepared mixed monolayer consisted of ionophore molecules covalently bonded to the electrode surface and dodecanethiol molecules. This procedure was used to prepare a dense monomolecular layer and avoid a pinhole formation. Dodecanethiol was chosen because of its ability to create a well-ordered monolayer and serve as an inert background for receptor molecules. Chain lengths of receptor tetralactam and dodecanethiol were similar, which help create the ordered monolayer.

The embedment method involved two steps. Firstly, electrodes were modified only by DDT to form a homogeneous lipophilic monolayer on the surface. Then the macrocycle possessed one lipophilic side chain (receptor 2 or 3; Figure 1) and was immobilised via hydrophobic and van der Waals interactions (*30*, *31*). The layer formed by this procedure was rather bimolecular.

The monolayer prepared by the covalent method was better stabilised than that prepared by embedment. The first method assumed the creation of a covalent bond, but hydrophobic interactions between lipophilic side chain of the ionophore and lipophilic chains of DDT also play some role in SAM stabilisation. We found that electrodes modified by this method are stable during CV measurements performed in the wide potential window (−500 to +50 mV). Mirsky et al. (*32*) postulated desorption of alkanethiol monolayer at electrode potentials −300 and −600 mV in the absence of alkanethiol in the bulk solution at pH 5.7. The loss of monolayer stability was observed when negative potential was applied for a duration longer than 15 min. In our work, negative potential was also applied to the modified electrodes, but time of exposure was considerable lower: less than 1 min in the case of CV (scan rate CV 500 mV s^{-1}) and OSWV (step potential 5 mV, frequency

100 Hz) and about 3 min in the case of impedance measurement. Because of this, we did not observe any influence of negative potential applying and monolayer stability was kept.

In the case of embedment modification, receptor molecules are bound to the electrode surface by weaker forces than in the case of covalent immobilisation, but Refs. (*30*, *31*) give examples of using the same procedure to obtain stable and reproducible SAMs.

Both modification procedures were monitored with OSWV. In order to display the role of tetralactam host in SAMs, the gold electrodes modified only with DDT was used. These electrodes were measured with CV and OSWV with $[Ru(NH_3)_6]^{3+}$ as redox marker. Obtained voltammograms were compared with the results obtained for electrodes coated additionally with tetralactam by both methods of modification (Figure S1 supplementary material). In the event of embedment technique of modification for electrodes coated with a mixed layer, the peak current of reduction/oxidation process of $[Ru(NH_3)_6]^{3+}$ was much lower in comparison with thiol monolayer (Figure S1A supplementary material). Access of $[Ru(NH_3)_6]^{3+}$ to the surface of electrodes modified by embedment was more hindered probably because of the bilayer structure of this SAM.

Covalent modification led to monolayer creation. In this case for electrodes coated with a mixed layer was observed higher peak current in comparison with the electrodes modified with thiol monolayer (Figure S1B supplementary material). The created mixed layer was less ordered than that formed by only one type of thiol molecules and access of redox marker ions was facilitated.

Comparison of both investigated mixed SAMs showed that for electrodes coated with embedment lower peak current was observed. Access of redox marker molecules to the bilayer-modified electrode surface was more hindered than that to the surface of electrodes modified covalently with mixed monolayer.

Similar results were obtained for electrodes modified with macrocyclic polyamine – also by covalent and embedment methods (*30*, *31*), where the same correlation appeared.

For investigated SAMs, EIS experiment was also performed. The results were displayed as the relation of the imaginary ($-Z''$) versus real (Z') impedance components plotted for various frequencies (the Nyquist plots $-Z''$ versus Z'). The equivalent circuit model used to fit the experimental data is shown in Figure 5(E). It consists of resistance solution R_s, constant phase element (CPE) Q_{dl}, charge transfer resistance R_{ct} and Wartburg element Z_w. The CPE (Q_{dl}) was used instead of the ideal capacitor in order to improve the fitting and minimise the errors (typical plot of fitting is shown in Figure S7 in the supplementary material). The CPE expressed the double-layer capacitance and its use is caused by a microscopic roughness or heterogeneity of gold electrode surface (*33*).

The impedance of CPE is given by:

$$Z_{CPE} = 1/(Y_0 j\omega)^n,$$

where Y_0 is CPE constant; $j = (-1)^{1/2}$; $\omega = 2\pi f$, f being the frequency of the applied ac potential; and n is a fractional parameter equalling a value from 0.5 (for an ideally porous electrode) to 1.0 (for a perfectly smooth electrode).

When $n = 1$, $Y_0 \equiv C_{dl}$ (capacity of double layer) and purely capacitive behaviour is obtained. A small deviation from 1.0 ($n > 0.9$) was observed in this study, which suggests that Y_0 parameter can be treated as a capacity of double layer.

Table S1 supplementary material showed values of Y_0 constant for investigated SAMs. The value of this parameter decreases with increases in the thickness of the SAM. The value of Y_0 for DDT monolayer prepared from 1.0 mM solution was similar to that obtained for covalent modification. It can be explained by the fact that receptor 1 used for this modification had a side chain (C11) with length similar to that of dodecanethiol chain (C12) and these two monolayers could have comparable thickness. The value of Y_0 for DDT monolayer prepared from 0.01 mM solution was higher than that obtained for embedment modifications. It showed that embedment modification leads to the formation of thicker SAM in comparison with DDT layer.

These results are in good agreement with the results obtained for OSWV (Figure S1 supplementary material).

Sensitivity of tetralactam SAMs towards acrylic acid

The determination of acrylic acid by gold electrodes modified with tetralactam by covalent and embedment methods has been examined using two techniques: CV and OSWV in 0.01 M KNO_3. Redox marker $[Ru(NH_3)_6]Cl_3$ was most suitable for the investigated system. The negatively charged $[Fe(CN)_6]^{3-/4-}$ was shown to be irreversible in the cases of investigated modifications. Moreover, this marker demands higher concentration of supporting electrolyte (0.1 M), which can decrease the interaction between the host and the anionic guest. Ruthenium complex can be used in lower concentrations of supporting electrolyte (0.01 M). Due to the reasons noted above, $[Ru(NH_3)_6]^{3+}$ was chosen.

The interaction between a tetralactam host immobilised on Au electrode surface by covalent and embedment methods and anion of acrylic acid were investigated by voltammetric techniques CV and OSWV (*34–37*). The measurements were performed in a pH 5.0 solution. Electrodes modified with covalent technique showed different peak current (from -0.39 to -1.07 μA) and

peak potential (from −184.0 to −343.0 mV) in 0.01 M KNO_3 solution containing 0.1 mM $[Ru(NH_3)_6]Cl_3$. Electrodes modified with embedment method also showed differentiation in peak maximum parameters obtained in 0.01 M KNO_3 solution containing 0.1 mM $[Ru(NH_3)_6]Cl_3$. For modification with receptor 2, peak current values were ranging from −0.51 to −0.67 μA and peak potential from −262.0 to −292.0 mV. For modification with receptor 3, peak current was ranging from −1.03 to −1.68 μA and peak potential from −143.0 to −163.0 mV. Because of this parameter, relative decreasing of peak current was used to evaluate their response. The ratio of OSWV peak current in the presence of different concentrations of acrylic acid (I_p) to that in the absence of acrylic acid ($I_{p,0}$; $I_p/I_{p,0} \times 100\%$) was plotted versus the acrylic acid concentration. Even though the modified electrodes studied showed different maximum current in 0.01 M KNO_3 solutions, all of them modified with the same method displayed similar sensitivity towards acrylic acid estimated using the relative current decreasing ($I_p/I_{p,0} \times 100\%$).

Electrodes modified by covalent method had similar detection limit, which was 1.0×10^{-5} M, but slightly different linearity region in comparison with the embedment modification with receptor 2. In the case of covalent modification, it was from 1.0×10^{-5} to 2.5×10^{-4} M, with slope −42.8%/decade (obtained from the plot $I_p/I_{p,0} \times 100\%$ versus $\log c$) and regression coefficient 0.976. In the case of embedment, it was from 1.0×10^{-5} to 1.0×10^{-3} M with slope −10.6%/decade and regression coefficient 0.930.

A stronger response towards acrylic acid was observed with electrodes modified by covalent method (Figure 3; Figure S2 supplementary material) in relation to those modified with embedment (Figure 4). The highest acrylic acid concentration studied (1.0×10^{-3} M) caused 67.5% current decrease in OSWV in the case of covalent modification and 21.3% for the electrodes modified by embedment. Electrodes modified with acyclic derivative (receptor 3) were also investigated. These electrodes prepared by embedment and measured under the same conditions of pH showed inconsiderable response towards acrylic acid (Figure S6 supplementary material). The CV showed lower sensitivity when compared with square-wave

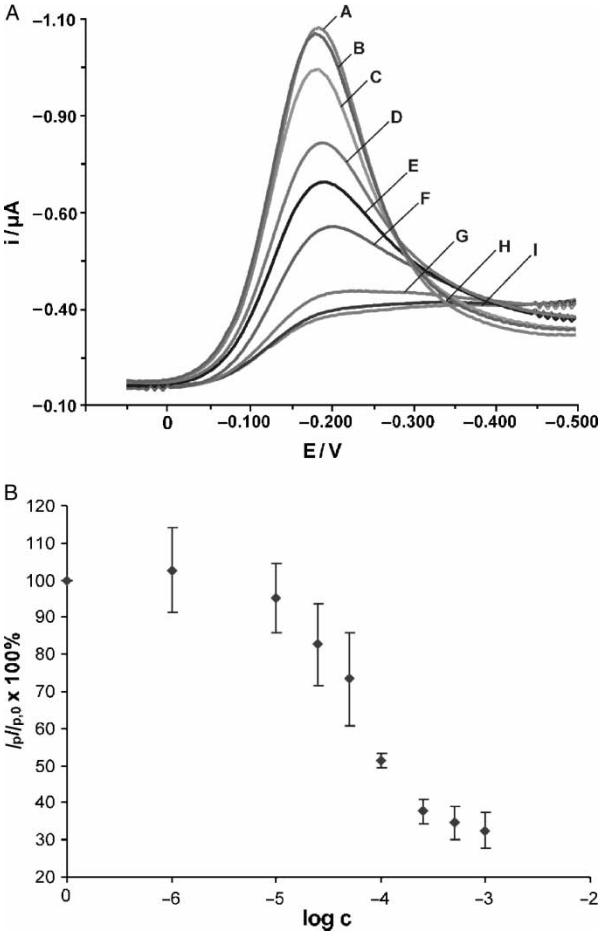


Figure 3. (A) The OSWV curves for $[Ru(NH_3)_6]^{3+}$ measured with electrodes modified by covalent method (receptor 1) in the presence of various concentrations of acrylic acid. The electrolyte composition: 0.01 M KNO_3 (pH 5.0), 0.1 mM $[Ru(NH_3)_6]^{3+}$. Step potential: 5 mV, square-wave frequency: 100 Hz, and square-wave amplitude: 25 mV. The concentration of the analyte was: (A) 0, (B) 1.0×10^{-6}, (C) 1.0×10^{-5}, (D) 2.5×10^{-5}, (E) 5.0×10^{-5}, (F) 1.0×10^{-4}, (G) 2.5×10^{-4}, (H) 5.0×10^{-4}, (I) 1.0×10^{-3} M. (B) The ratio of OSWV peak current in the presence of different concentrations of acrylic acid (I_p) to that in the absence of acrylic acid ($I_{p,0}$) as a function of the acrylic acid concentration. The currents were measured at the peak potential in OSWV curves in the solution with no analyte. $E_{p,0} = -243$ mV, $n = 3$, 5.4% < SD < 15.0%.

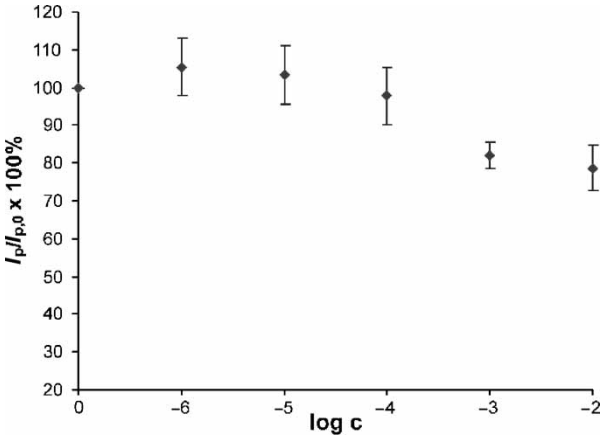


Figure 4. The ratio of OSWV peak current with electrodes modified by embedment technique with receptor 2 in the presence of different concentrations of acrylic acid (I_p) to that in the absence of acrylic acid ($I_{p,0}$) as a function of the acrylic acid concentration. The currents were measured at the peak potential in OSWV curves in the solution with no analyte. $E_{p,0} = -292$ mV, $n = 3$, 3.6% < SD < 7.7%.

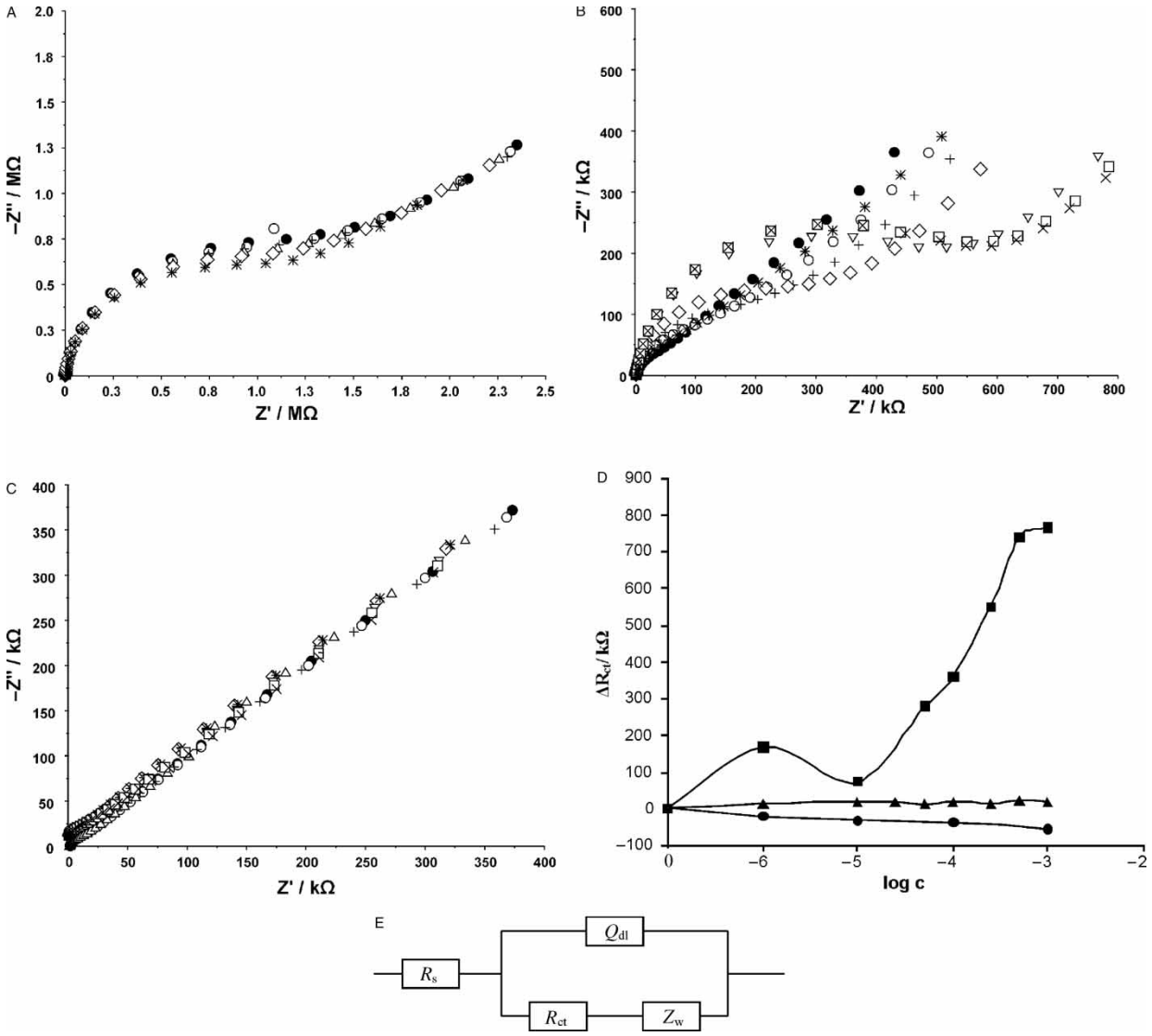


Figure 5. Impedance plots of 0.1 mM $[Ru(NH_3)_6]^{3+}$ measured in the absence and presence of different concentrations of acrylic acid in the solution of 0.01 M KNO_3 (A) pH 3.0, (B) pH 5.0, (C) pH 6.2. (D) Plot of relative change of R_{ct} with concentration of analyte for solutions of pH 3.0 (▲), 5.0 (■), 6.2 (●). (E) Equivalent circuit used to fit the experimental data: R_S, the solution resistance; Q_{dl}, constant phase element; R_{ct}, charge transfer resistance; Z_W, Wartburg element.

voltammetry. Important advantage of OSWV is the ability to suppress the background and, because of that, it is more sensitive and more suitable for quantitative measurements. The results obtained for CV and OSWV are presented in the Figures S2 supplementary material and Figure 3.

EIS was used to detect acrylic acid with electrodes modified by covalent method. Results obtained for EIS were in good agreement with that for OSWV. The observed range of response was similar in both cases. Results obtained for EIS are presented in Figure 5. The equivalent circuit model used to fit the experimental data is shown in Figure 5(E). It consists of resistance solution R_S, CPE Q_{dl}, charge transfer resistance R_{ct} and Wartburg element Z_w. Parameters such as solution resistance and the CPE should remain almost constant for measurements performed in the absence and presence of a faradaic process. Determination of these parameters in the absence of a redox reaction and using them as initial estimates in the presence of the reaction help to reduce the error in the fit. However, faradaic impedance spectroscopy technique using a redox probe molecule and measured at the formal potential of the redox probe can reveal a dependence of electron transfer resistance in the SAM during complex formation. Formal potential of the redox marker was chosen as a potential at which the data were collected on the basis of Refs. (*38–40*).

As a control experiment, electrodes modified only with DDT were used (Figure S4 supplementary material).

These electrodes showed only negligible response towards the analyte in the solution of pH 5.0. This proved that only the tetralactam host presence was responsible for recognition process.

Electrodes modified with acyclic derivative (receptor 3) were also investigated. These electrodes, prepared by embedment technique and measured under the same conditions of pH, showed inconsiderable response towards acrylic acid (Figure S6 supplementary material). This suggested that only interaction between macrocyclic tetralactam and acrylic acid is sufficient.

Mechanism of response

In the present paper, the interaction between acrylic acid and tetralactam molecules immobilised on the surface of gold electrodes either by the covalent or embedment method was investigated. CV, OSWV and EIS measurements were performed in the presence of 0.01 M KNO_3 used as supporting electrolyte. Appropriate pH values (3.0, 5.0 and 6.2) were obtained by the addition of KOH or HNO_3 solution. Because of interference and suppressing of response, no buffer solution was used.

At pH 5.0, 85% analyte existed as anionic form and 15% as neutral form in the solution, whereas tetralactam existed in the layer on the electrode surface as a neutral compound. This ionophore and analyte in ionic or neutral form can interact by hydrogen bond formation. Tetralactam macrocycle has four amide fragments that can form strong H-bonds and can serve both as donors and acceptors of such bonds. $\pi-\pi$ interactions between double bonds of analyte and aromatic rings of host molecule also can play some role (*16*).

Geometry optimisation of a number of different conformations of the macrocycle in vacuum using CaChe Workspace programme (CaChe Worksystem Pro Version 7.5.0.85) and AM1 geometry procedure (MOPAC 2002 Version 2.5.3, J. J. P. Stewart, Fujitsu Limited, Tokyo, Japan) showed that the most favourable conformation of the host molecule is when all four amide —NH group (acceptors of H-bond) are oriented inside the macrocycle cavity (− 185.10 kJ). Conformation with one —NH group oriented outside the cavity is slightly less favourable (− 172.77 kJ). These results are in good agreement with the similar calculations in $CHCl_3$ conducted by Kleefish et al. (*16*) and structures obtained by X-ray crystallography (*41*). These results indicate the strong H-bond-accepting character of the investigated macrocycle cavity.

Acrylic acid in dissociated form possesses stronger electron donor characters and, because of that, stronger affinity to the tetralactam cavity in comparison with the neutral form. That suggests that observed response was caused more by the anionic than the neutral form of analyte.

In order to support the above conclusion, OSWV and EIS experiments in a solution of pH 6.2 were conducted. In these conditions, about 100% of analyte existed in anionic form and the expected response of the sensor should be improved. However, electrodes measured in solution at higher pH showed considerably lower response for acrylate anion (Figure 5; Figure S5 supplementary material). A possible explanation for this phenomenon can be the interaction of the ionophore with OH^- ions, which can also be strong H-bond donors and have high affinity to the tetralactam cavity.

Measurement conducted by EIS at pH 3.0 (when analyte exists in solution in neutral form) showed no response of electrodes modified with covalent method towards acrylic acid. These results showed that pH 5.0 was optimal for the detection of the analyte and confirmed the conclusion that observed interaction occurs between the ionophore and the anionic forms of analyte.

The working principle of the sensor presented suggests that it can be assigned to 'ion-channel' or 'ion-channel-mimetic' sensors. Umezawa and co-workers (*42–44*) who have introduced these types of sensors have distinguished two types of such sensors according to the mechanism of response: intermolecular and intramolecular ion-channel sensors. In the first group, electrostatic ion–ion interaction (electrostatic attraction or repulsion) and physical blocking of the intermolecular voids prevents the access of redox marker to the electrode surface. Binding ionic analytes to the synthetic receptor layer changes the total charge of the layer and its permeability for marker ions. In intramolecular ion-channel sensors, the access of markers to electrode surface through the intramolecular cavity of receptors can be blocked by the formation of inclusion-type complexes with an analyte.

In measuring conditions, the acrylate anion can interact with neutral tetralactam molecules to form a negatively charged complex. This may give negative charge to the layer and increase attraction between the electrode and the positively charged redox marker $[Ru(NH_3)_6]^{3+}$. However, a sensor reported decreasing of peak current. Probably the physical blocking of intermolecular spaces prevented the access of marker ions to the electrode and played a decisive role in the generation of the investigated sensor response. This can be explained by the idea of an intermolecular ion-channel mechanism (*42–44*).

Supramolecular complex formations not only block reaction of electron transfer between the electrode and the marker molecules but also affect its kinetics. Reversibility of the reduction/oxidation process of $[Ru(NH_3)_6]^{3+}$ decreased. So the maximum of peak current observed by OSWVs decreased and shifted to more negative potential values. In the case of covalent modification investigated in this work, the highest acrylic acid concentration studied (1.0×10^{-3} M) caused 67.5% current decrease in OSWV and a slight shift of peak potential. In the case of electrodes modified by embedment method, lower current decrease

(21.3%) but higher negative shift of peak potential was observed. This phenomenon can be connected with different characters of two investigated monolayers. The embedment technique provided more flexibility of ionophore molecules in comparison with the covalent method, which can entail different characteristics of a complex formation. Upon increasing acrylate anion concentration, the faradaic current of redox reaction decreased for electrodes modified by either the covalent or the embedment method. The size of tetralactam cavity estimated by AM1 MOZYME geometry optimisation (5.845 Å – the smallest width) and estimated from Corey–Pauling–Koltun atomic (CPK) model (6.4 Å) is large enough to hold the analyte (5.1 Å – CPK model) but not large enough for the marker $[Ru(NH_3)_6]^{3+}$ (6.4 Å (*45*)) to penetrate through. This also confirms the conclusion of investigated sensor work according to the intermolecular ion-channel sensor mechanism.

Gold electrodes coated with host molecule by covalent method showed higher sensitivity than those coated by embedment modification (Figures 3 and 4). Embedment technique provided higher flexibility of prepared layer. Macrocycle interacts with thiol layer via non-covalent interaction and has the possibility to take the most suitable conformation for interaction with analyte. The covalent technique did not provide such 'conformational freedom'. Because of the above reasons, higher sensitivity for embedment modification was expected. However, obtained results were different.

Measured tetralactam is a 32-membered macrocycle that possesses six benzene ring fragments and, as the CPK model showed, is rather rigid and does not have the ability to adopt its conformation. Another possible explanation can be the difference in the structure of two investigated layers. The covalent technique makes it possible to create a monolayer containing tetralactam molecules. In the case of embedment technique, a bilayer is formed and ionophore molecules recede from the electrode surface, which can explain the decrease of sensitivity.

In this case, a crucial factor can also be the density of electrode surface coverage by the host molecules, which for the covalent method can be higher. Investigated tetralactam after modification is covalently bonded to the electrode surface via one side chain. Embedment assumes the attachment of the macrocycle by hydrophobic and van der Waals interactions between the alkanethiol monolayer and the aliphatic side chain of host molecule. Measured tetralactam possesses only one side chain and, because of that, such prepared SAMs were less stable and less reproducible in comparison with the covalent method.

A similar comparison of these two techniques of immobilisation was made using polyamine macrocycle (*30*, *31*). This 30-membered macrocycle possesses two aromatic rings as fragments of macrocycle. Electrodes modified with this bigger and significantly more flexible molecule by embedment showed better sensitivity than those coated by covalent technique. Moreover, these macrocycles formed stable and reproducible SAMs via six aliphatic side chains versus the investigated tetralactam that possessed one side chain.

Conclusions

It was proved that tetralactam macrocycle can be used as the host molecule of chemically modified gold electrodes destined for the detection of acrylic acid in water solution.

The interaction between the tetralactam host and the acrylate guest could be observed using OSWV and EIS.

The covalent method of host immobilisation on the gold electrode surface was more suitable than the embedment method. Electrodes modified by covalent technique were characterised by better sensor-to-sensor repeatability in comparison with those modified by embedment.

Faradaic impedance spectroscopy as well as CV and OSWV was used to investigate reported systems, and based on the results obtained for these methods intermolecular ion-channel mechanism of response was proposed.

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