Talanta 85 (2011) 2470–2478

Contents lists available at ScienceDirect

Talanta

journal homepage: www.elsevier.com/locate/talanta

(Oligo)thienyl-imidazo-benzocrown ether derivatives: Synthesis, photophysical studies and evaluation of their chemosensory properties

Rosa M.F. Batista [a], Elisabete Oliveira [b], Susana P.G. Costa [a], Carlos Lodeiro [b,c], M. Manuela M. Raposo [a,*]

[a] Centre of Chemistry, University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal
[b] BIOSCOPE Group, Physical-Chemistry Department, Faculty of Science, University of Vigo, Campus of Ourense, E-34002, Spain
[c] REQUIMTE, Department of Chemistry, Faculty of Sciences and Technology, New University of Lisbon, 2829-516, Monte de Caparica, Portugal

ARTICLE INFO

Article history:
Received 18 May 2011
Received in revised form 26 July 2011
Accepted 29 July 2011
Available online 9 August 2011

Dedicated to the Centenary of the Portuguese Chemical Society.

Keywords:
Benzo-15-crown-5 ether
(Oligo)thiophene
Imidazole
Fluorescent chemosensors
Hg^{2+}
Pd^{2+}
CHEF effect

ABSTRACT

A series of novel (oligo)thienyl-imidazo-benzocrown ethers were synthesised through a simple method and evaluated as fluorimetric chemosensors for transition metal cations. Interaction with Ni^{2+}, Pd^{2+}, and Hg^{2+} in ACN/DMSO solution (99:1) was studied by absorption and emission spectroscopy. Chemoselectivity studies in the presence of Na^{+} were also carried out and a fluorescence enhancement upon chelation (CHEF) effect was observed following Hg^{2+} complexation. Considering that most systems using fluorescence spectroscopy for detecting Hg^{2+} are based on the complexation enhancement of the fluorescence quenching (CHEQ) effect, the present work represents one of the few examples for sensing of Hg^{2+} based on a CHEF effect.

1. Introduction

Fluorescence analysis has a number of advantages in comparison with other optical methods; it is highly sensitive and of simple execution and can be used over a wide range of investigated materials [1]. Because of the high demand in analytical chemistry, clinical biochemistry, medicine, environmental analysis, etc., numerous studies have reported fluorescent chemosensors for cations [2].

Most of the recent research progress in this area has focused on sensing and selectively removing heavy transition metal (HTM) ions such as Cu^{2+}, Pb^{2+}, Cd^{2+} and Hg^{2+} [3a–c] that are highly toxic to living plants and animals, even at very low concentration [3d,e]. Among them, Hg^{2+} or the lipophilic methyl-mercury derivative (obtained from conversion of elemental mercury by microbial action on the sediments or soil) once formed can be taken up in the food chain of aquatic organisms doing huge harm to humans and nature [4]. Accordingly, the need for analytical methods for the sensitive and selective determination of mercury is of topical interest. Numerous examples of fluorescent chemosensors for Hg^{2+} were reported [3a–c,5,6] and most systems using fluorescence spectroscopy for detecting Hg^{2+} are based on the complexation enhancement of the fluorescence quenching (CHEQ) effect [5]. Such quenching is disadvantageous because it hampers a temporal separation of spectrally similar complexes with time-resolved fluorometry and because it produces lower output signal upon complexation. On the other hand, only a few fluorescent chemosensors are based on fluorescence enhancement upon chelation (CHEF) effect [6].

Palladium is widely used in various materials such as dental crowns, catalysts, fuel cells, and jewelry [7a–c]. Automobile catalytic converters apparently release a significant quantity of palladium to the roadside environment where dust samples collected from broad-leaved plants were found to contain palladium in about 0.3 ppm and rain may also wash Pd into local water systems [7d]. Pd-catalyzed reactions represent powerful transformations for the synthesis of complex molecules [7e–h], but despite the frequent and fruitful use of such reactions, a high level of residual palladium (typically 300–2000 ppm) is often found in the resultant product, which thus may be a health hazard [7i].

* Corresponding author. Tel.: +351 253 604381; fax: +351 253 604382.
E-mail addresses: clodeiro@fcou.vigo.es (C. Lodeiro), mfox@quimica.uminho.pt (M.M.M. Raposo).

0039-9140/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.talanta.2011.07.107

Governmental restrictions on the levels of residual heavy metals in end products are very strict, the threshold for palladium in drugs being 5–10 ppm [7j]. Therefore, methods are urgently needed for sensitive and selective detection for palladium in a high throughput fashion. The typical analytical methods for palladium include atomic absorption spectrometry, plasma emission spectroscopy, solid phase micro-extraction-high performance liquid chromatography and X-ray fluorescence [7k–m] which all suffer from the high cost of instrumentation and requirement of highly trained technicians. A fluorescence method would be more desirable because of the easy sample preparation and convenient operation. As a strong fluorescence quencher, Pd^{2+} could be detected by fluorescent ligands through fluorescence quenching [7n–r].

Crown ether derivatives occupy a special position among receptors and are widely used in the design of new chemosensors based on their unique ability to combine with the cations of alkaline metals, their fairly high selectivity and accessibility. In addition to alkaline metals, crown ethers are also effective complexing reagents for alkaline-earth and transition metal ions [8].

Recently we reported the synthesis and characterization of novel heterocyclic chemosensors bearing crown ether, anthraquinone, (oligo)thiophene, (benz)imidazole and benzoxazole binding sites for anion and metal ion detection [9]. Thiophene moieties are also often used for binding heavy or transition metal cations. Since a sulphur atom is considered as a "soft" donor atom in a chelating reagent, it generally increases the sensor's affinity and selectivity for "soft" metals such as Hg^{2+} and Pd^{2+}. Earlier we have shown that the combination of thiophene and oxocrown ether moieties could modulate the sensor behaviour of the resulting structures in order to obtain selective Hg^{2+} and Pd^{2+} fluorescent chemosensors [9c,e], taking advantage of cooperative effects in solution for the simultaneous exploration of alkaline/alkaline earth ions in the presence of transition metal ions. The use of oxocrown instead of thiacrown ether was intended to force the interaction through the sulphur atom of the thiophene. Also the introduction of an imidazole heterocycle in the skeleton of (oligo)thiophene derivatives increased the fluorescence of the ligands [9a].

Following our current interests on colorimetric and fluorimetric chemosensors and having in mind our earlier studies concerning the chemosensory properties of heterocyclic crown ether derivatives [9c,d,i], five novel heterocyclic systems (**5**–**7**) containing functionalized (oligo)thiophene spacers and a imidazobenzocrown ether binding moiety were designed and synthesized in order to tune their photophysical properties and evaluate their chemosensory ability.

2. Experimental

2.1. Chemicals

4-Amino-5-nitrobenzo-15-crown-5 (**4**), 2-formylthiophene **1** and 5-formyl-2,2′-bitiophene (**2a**) were purchased from Aldrich and used as received. The synthesis of 5-methoxy-5′-formyl-2,2′-bithiophene (**2b**) [10], 5-cyano-5′-formyl-2,2′-bithiophene (**2c**) [9a] and 5-formyl-2,2′:5′,2″-terthiophene (**3**) [11] has been described by us elsewhere. Reaction progress was monitored by thin layer chromatography (0.25 mm thick precoated silica plates: Merck Fertigplatten Kieselgel 60 F254.

In the titration experiments, all the cations were added in the form of tetrafluroborate salts, and were purchased from Sigma–Aldrich Chemical and Strem-Chemical without further purifications. All were stored in a vacuum desiccator containing self-indicating silica gel and fully dried before using. DMSO was dried over CaH_2 and then distilled under reduced pressure. Other organic solvents were purified by standard methods.

2.2. Instrumentation

NMR spectra were obtained on a Varian Unity Plus Spectrometer at an operating frequency of 300 MHz for ^1H and 75.4 MHz for ^{13}C or a Bruker Avance III 400 at an operating frequency of 400 MHz for ^1H and 100.6 MHz for ^{13}C using the solvent peak as internal reference. The solvents are indicated in parenthesis before the chemical shift values (δ relative to TMS and given in ppm). Mps were determined on a Gallenkamp apparatus. Infrared spectra were recorded on a BOMEM MB 104 spectrophotometer. Mass spectrometry analyses were performed at the "C.A.C.T.I. -Unidad de Espectrometria de Masas" at the University of Vigo, Spain. UV–vis absorption spectra (220–800 nm) were obtained using a Perkin Elmer lambda 35 spectrophotometer and fluorescence emission on a Perkin Elmer LS45.

2.3. General procedure for the synthesis of compounds **5**–**7**

A solution of 4-amino-5-nitrobenzo-15-crown-5 (**4**) (1 equiv.) and formyl-(oligo)thiophene **1**–**3** (1 equiv.) in DMSO (3 mL) was treated with $Na_2S_2O_4$ (3 equiv.), dissolved in a small volume of water, and heated at 80 °C with stirring for 15 h. The mixture was then cooled to room temperature and neutralized with NH_4OH 5 M. For compounds **6** and **7**, a precipitate was formed and filtrated, washed with water and diethyl ether and dried to give the expected pure product. For compound **5**, the mixture was extracted with chloroform. The organic phase was dried with magnesium sulphate and evaporated.

2.4. 2-(Thien-2′-yl)-imidazo[4,5-f]benzo-15-crown-5 (**5**)

Brown oil (98%). UV (DMSO): λ_{max} nm (log ε) 343.0 (4.41), 259.5 (3.83). IR (KBr) ν 3439, 2950, 2874, 1631, 1593, 1486, 1453, 1428, 1335, 1277, 1227, 1184, 1133, 1058, 946, 850, 717 cm^{-1}. ^1H NMR (DMSO-d_6 + TFA) δ 3.63 (s, 8H, 4xCH_2), 3.82 (s, 4H, 2xCH_2), 4.10 (s, 4H, 2xCH_2), 7.14 (broad s, 2H, 4-H and 5-H), 7.30 (m, 1H, 4′-H), 7.89-7.93 (m, 2H, 3′-H and 5′-H). ^{13}C NMR (DMSO-d_6 + TFA) δ 68.68 (2xCH_2), 68.96 (2xCH_2), 69.68 (2xCH_2), 70.41 (2xCH_2), 98.13 (C4 + C5), 128.67 (C4′, C3a and C5a), 129.13 (C5′ and C2′), 130.85 (C3′), 143.43 (C2), 147.71 (C4a and C4b). MS (FAB) *m*/*z* (%): 391 ([M+H]$^+$, 100), 390 (M$^+$, 54), 307 (26), 289 (13), 155 (22), 154 (76). HRMS: (FAB) *m*/*z* (%) for $C_{19}H_{22}N_2O_5S$; calcd 391.1328; found 391.1327.

2.5. 2-(2′,2″-Bithien-5′-yl)-imidazo[4,5-f]benzo-15-crown-5 (**6a**)

Yellow solid (90%). Mp: 230–232 °C. UV (DMSO): λ_{max} nm (log ε) 386.5 (4.25), 259.5 (3.64). IR (Nujol) ν 3460, 2724, 1634, 1488, 1353, 1309, 1283, 1247, 1227, 1202, 1169, 1139, 1050, 975, 945, 841, 804, 722 cm^{-1}. ^1H NMR (DMSO-d_6 + TFA) δ 3.63 (s, 8H, 4xCH_2), 3.82 (s, 4H, 2xCH_2), 4.15 (s, 4H, 2xCH_2), 7.16–7.19 (m, 3H, 4-H, 5-H and 4″-H), 7.53 (dd, 1H, J = 3.6 and 0.9 Hz, 3″-H), 7.56 (d, 1H, J = 3.9 Hz, 3′-H), 7.68 (dd, 1H, J = 5.4 and 0.9 Hz, 5″-H), 7.99 (d, 1H, J = 3.9 Hz, 4′-H). ^{13}C NMR (DMSO-d_6 + TFA) δ 68.60 (2xCH_2), 69.02 (2xCH_2), 69.64 (2xCH_2), 70.52 (2xCH_2), 97.21 (C4 and C5), 123.35 (C2′), 125.41 (C3′), 126.29 (C3″), 127.26 (C3a and C5a), 127.81 (C5″), 128.95 (C4″), 132.45 (C4′), 134.75 (C2″), 141.55 (C2), 142.22 (C5′), 148.71 (C4a and C4b). MS (FAB) *m*/*z* (%): 473 ([M+H]$^+$, 91), 472 (M$^+$, 35), 307 (35), 289 (17), 282 (13), 155 (31), 154 (100). HRMS: (FAB) *m*/*z* (%) for $C_{23}H_{24}N_2O_5S_2$; calcd 473.1205; found 473.1208.

2.6. 2-(5″-Methoxy-2′,2″-bithien-5′-yl)-imidazo[4,5-f]benzo-15-crown-5
(***6b***)

Green solid (96%). Mp: 160–162 °C. UV (DMSO): λ_{max} nm (log ε) 396.0 (4.29), 312.0 (3.48). IR (KBr) ν 3369, 1635, 1511, 1488, 1451, 1425, 1345, 1304, 1251, 1129, 1053, 988, 941, 851 cm^{-1}. ^{1}H NMR (DMSO-d_6) δ 3.61–3.64 (m, 8H, 4xCH_2), 3.79–3.81 (m, 4H, 2xCH_2), 3.89 (s, 3H, OCH_3), 4.06-4.08 (m, 4H, 2xCH_2), 6.33 (d, ^{1}H, J = 3.9 Hz, 4″-H), 7.04-7.06 (m, 3H, 3″-H, 4-H and 5-H), 7.16 (d, 1H, J = 3.9 Hz, 4′-H), 7.60 (d, 1H, J = 3.9 Hz, 3′-H). ^{13}C NMR (DMSO-d_6) δ 60.44 (OCH_3), 68.88 (2xCH_2), 68.94 (2xCH_2), 69.79 (2xCH_2), 70.37 (2xCH_2), 98.74 (C4), 99.58 (C5), 105.18 (C4″), 122.00 (C2″), 122.85 (C3″), 123.11 (C3′), 126.56 (C4′), 129.74 (C5′), 130.74 (C3a and C5a), 138.46 (C2′), 144.92 (C2), 146.50 (C4a and C4b), 165.44 (C5″). MS (FAB) m/z (%): 503 ([M+H]$^+$, 99), 502 (M$^+$, 74), 307 (36), 289 (17), 155 (30), 154 (100). HRMS: (FAB) m/z (%) for $C_{24}H_{26}N_2O_6S_2$; calcd 503.1311; found 503.1315.

2.7. 2-(5″-Cyano-2′,2″-bithien-5′-yl)-imidazo[4,5-f]benzo-15-crown-5
(***6c***)

Orange solid (80%). Mp: 232–234 °C. UV (DMSO): λ_{max} nm (log ε) 411.0 (4.25), 317.5 (3.71), 278.0 (3,64). IR (KBr) ν 3412, 2217, 1635, 1490, 1435, 1346, 1301, 1276, 1130, 1052, 944, 809 cm^{-1}. ^{1}H NMR (DMSO-d_6 + TFA) δ 3.63 (s, 8H, 4xCH_2), 3.82 (s, 4H, 2xCH_2), 4.13 (s, 4H, 2xCH_2), 7.16 (s, 2H, 4-H and 5-H), 7.63 (d, 1H, J = 3.9 Hz, 3″-H), 7.72 (d, 1H, J = 3.9 Hz, 3′-H), 7.93 (d, 1H, J = 3.9 Hz, 4′-H), 8.01 (d, 1H, J = 3.9 Hz, 4″-H). ^{13}C NMR (DMSO-d_6 + TFA) δ 68.66 (2xCH_2), 68.95 (2xCH_2), 69.67 (2xCH_2), 70.49 (2xCH_2), 97.79 (C4 and C5), 107.43 (C5″), 114.03 (CN), 125.95 (C3″), 128.04 (C3′), 128.47 (C3a), 128.95 (C5a), 130.44 (C4′), 137.55 (C2′), 139.01 (C5′), 140.50 (C4″), 142.00 (C2), 142.50 (C2″), 148.19 (C4a and C4b). MS (FAB) m/z (%): 498 ([M+H]$^+$, 24), 497 (M$^+$, 10), 307 (39), 289 (18), 282 (10), 155 (37), 154 (100). HRMS: (FAB) m/z (%) for $C_{24}H_{23}N_3O_5S_2$; calcd 498.1157; found 498.1162.

2.8. 2-(2′,2″:5″,2‴-terthien-5′-yl)-imidazo[4,5-f]benzo-15-crown-5
(***7***)

Orange solid (81%). Mp: 238–240 °C. UV (DMSO): λ_{max} nm (log ε) 416.0 (4.37), 259.5 (3.80). IR (Nujol) ν 3498, 3065, 1636, 1302, 1277, 1250, 1206, 1171, 1141, 1100, 1053, 1013, 977, 938, 835, 793, 700 cm^{-1}. ^{1}H NMR (DMSO-d_6 + TFA) δ 3.63 (s, 8H, 4xCH_2), 3.82 (s, 4H, 2xCH_2), 4.13 (s, 4H, 2xCH_2), 7.12–7.14 (m, 1H, 4‴-H), 7.18 (s, 2H, 4-H and 5-H), 7.35 (d, 1H, J = 3.6 Hz, 3″-H), 7.40 (d, 1H, J = 3.3 Hz, 3‴-H), 7.49 (d, 1H, J = 3.6 Hz, 4″-H), 7.56–7.59 (m, 2H, 3′-H and 5‴-H), 7.95 (d, 1H, J = 4.0 Hz, 4′-H). ^{13}C NMR (DMSO-d_6 + TFA) δ 68.61 (2xCH_2), 68.99 (2xCH_2), 69.64 (2xCH_2), 70.47 (2xCH_2), 97.47 (C4 and C5), 124.66 (C2′), 124.97 (C3‴), 125.31 (C3″), 125.43 (C3′), 126.42 (C5‴), 127.04 (C4″), 127.17 (C3a and C5a), 128.58 (C4‴), 131.64 (C4′), 133.39 (C2″), 135.50 (C2‴), 137.35 (C5″), 140.90 (C5′), 141.87 (C2), 148.41 (C4a and C4b). MS (FAB) m/z (%): 555 ([M+H]$^+$, 100), 554 (M$^+$, 41), 307 (25), 260 (42), 155 (17), 154 (80). HRMS: (FAB) m/z (%) for $C_{27}H_{26}N_2O_5S_3$; calcd 555.1082; found 555.1083.

*2.9. General procedure for the chemosensing studies with compounds **5**–**7***

The linearity of the fluorescence emission vs. concentration was checked in the concentration range used (10^{-4} to 10^{-6} M). A correction for the absorbed light was performed when necessary. All spectrofluorimetric titrations were performed as follows: stock solutions of the compounds **5**–**7** (*ca.* 10^{-3} M) were prepared in a 50 mL volumetric flask with UVA-sol ACN/DMSO (99:1). The titration solutions were prepared by appropriate dilution of stock solutions. Titrations of the compounds were carried out at room temperature by addition of microliter amounts of standard solutions of the cations (Na^+, Ni^{2+}, Pd^{2+}, Hg^{2+}) in acetonitrile. Quartz cuvettes with 1 cm path and 3 mL volume were used for all experiments. All other chemicals were of reagent grade and used as supplied without further purification [12].

Luminescence quantum yields were measured using a solution of quinine sulphate in sulphuric acid (0.1 M) as a standard [Φ_F = 0.54] [13].

3. Results and discussion

3.1. Synthesis

Formyl-(oligo)thiophenes **1–3** were used as precursors in the synthesis of fused imidazo-benzocrown ethers **5–7**, in order to evaluate the influence of the different π-conjugated bridge and the electronic nature of the substituent groups on the optical and sensing properties of the new compounds. Recently a mild and versatile method for 2-benzimidazole synthesis was reported through a one step reaction involving $Na_2S_2O_4$ reduction of *o*-nitroanilines in the presence of pyridyl, quinolyl and thienylpyrrolyl aldehydes [14] in DMSO at 80 °C. To the best of our knowledge, this is the first time that this synthetic methodology is applied in order to prepare imidazo-benzocrown ether derivatives using as precursors (oligo)thiophene aldehydes and an *o*-nitroaminobenzocrown ether derivative. Therefore, heterocyclic crown ethers **5–7** were obtained in good to excellent yields (80–98%) through this synthetic methodology (Scheme 1) and the structures of these new chromophores were unambiguously confirmed by their analytical and spectral data (Table 1). Aldehyde precursors were commercially available (**1**, **2a**) or synthesised as reported previously by some of us (**2b-c**, **3**) [9a,10,11].

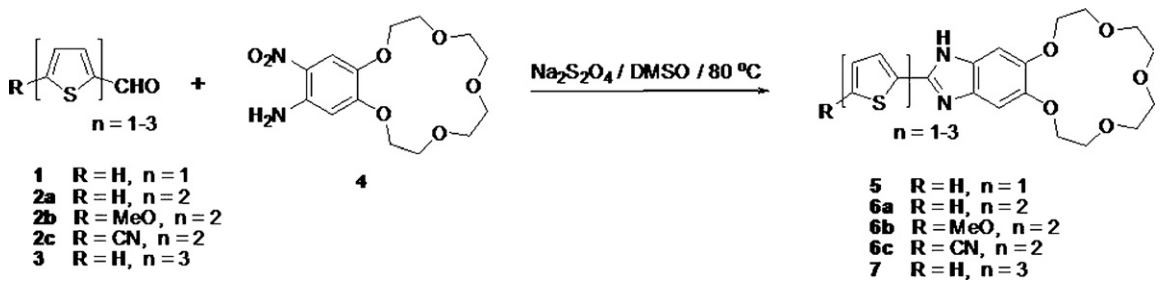
3.2. Absorption and emission studies

The electronic absorption and emission spectra of compounds **5–7** were obtained in ACN/DMSO (99:1) solution (Table 1). Compounds **5–7** were excited at the wavelength of maximum absorption, being $\lambda_{abs} = \lambda_{exc}$. The position of the bands was strongly influenced by the length of the π-conjugated bridge and the electronic nature of the substituents (hydrogen, methoxy and cyano) at the bithienyl moiety. The wavelength of maximum absorption for compounds **5**, **6a** and **7** was shifted to longer wavelength as the number of thiophene units increased, as expected from the increase in conjugation (Fig. 1A) [9c,d,f,15].

Regarding the electronic nature of the substituent in compounds **6**, a red-shift was observed for compounds **6b** (λ_{max} = 390 nm) and **6c** (λ_{max} = 400 nm) relative to the unsubstituted **6a** (λ_{max} = 377 nm), due to the strong inductive and/or conjugative effect of the methoxy and cyano groups (Fig. 1B). In general, the stronger the donor and/or acceptor group, the smaller the energy difference between ground and excited states, and the longer the wavelength of absorption.

The same trend was observed in the emission spectra of these compounds as the position of the wavelength of maximum emission was red-shifted, *ca.* 48–63 nm for each added thiophene. The synthesized compounds showed large Stokes' shift (the lowest being 63 nm for **5** and the highest 140 nm for **6c**). An increasing trend in the Stokes' shifts could be observed along the series **5** (thiophene) < **6a** (bithiophene) < **7** (terthiophene).

The relative fluorescence quantum yields were determined using quinine sulphate in sulphuric acid as standard and



Scheme 1. Synthesis of imidazo[4,5-*f*]benzo-15-crown-5 ethers **5**-**7**.

Table 1
Yields, IR, UV–vis absorption and emission data for crown ethers 5–7.

Compounds	R	*n*	Yield (%)	IR ν (cm^{-1})	UV–vis λ_{abs} (nm)[c]	Fluorescence		
						λ_{em} (nm)[c]	Φ_F	Stokes' shift (nm)
5	H	1	98	3439[a]	337	409	0.26	63
6a	H	2	90	3460[b]	377	463	0.57	86
6b	OMe	2	96	3369[a]	390	463	0.46	73
6c	CN	2	81	3498[b]	400	540	0.47	140
7	H	3	80	3412[a]	405	505	0.12	100

[a] For the NH stretching band (recorded in KBr).
[b] For the NH stretching band (recorded in Nujol).
[c] In ACN/DMSO (99:1) solution.

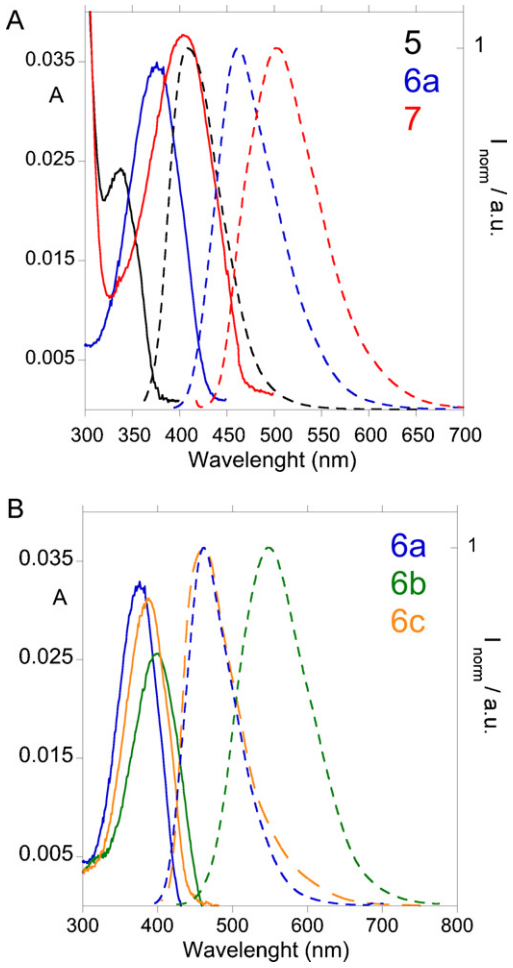


Fig. 1. Absorption (full line) and emission (dashed line) spectra of A) **5**, **6a** and **7** and B) **6a**–**c** in ACN/DMSO (99:1) (λ_{exc} **5** = 337 nm; λ_{exc} **6a** = 377 nm; λ_{exc} **6b** = 390 nm; λ_{exc} **6c** = 400 nm; λ_{exc} **7** = 405 nm; *T* = 293 K).

compounds **5–7** exhibited moderate to good fluorescence quantum yields. As expected, due to a further extension of the conjugated π-system, there was an increase in the fluorescence quantum yield as a second thiophene was introduced at the π-conjugated bridge (**5**, Φ_F = 0.26 and **6a**, Φ_F = 0.57). On the other hand, the heavy atom induced spin-orbit coupling by the sulphur atoms can give raise to a very efficient intersystem crossing mechanism, thus lowering the emission [15,16]. Moreover, azomethine nitrogens contribute to the heavy atom effect concomitant with the increased degree of conjugation [16c]. Also, the different bridges (thiophene, bithiophene and terthiophene) should exhibit different degrees of torsion between the thiophene units, which leads to variations in the effective conjugation length, affecting the planarity of the whole heteroaromatic system [16d]. In our case, we believe that a combination of the above mentioned effects could be responsible for the strong decrease in the fluorescence quantum yield (Φ_F = 0.12) of the terthiophene derivative **7**.

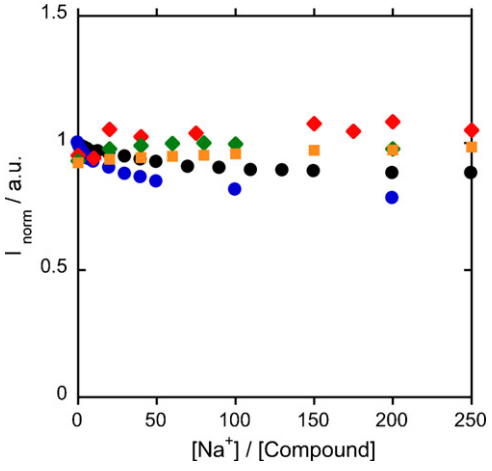


Fig. 2. Na^+ titration for compounds **5**–**7** in ACN/DMSO (99:1). Values taken at the maxima of the emission spectra: 409 nm (● **5**), 463 nm (● **6a**), 463 nm (■ **6b**), 540 nm (◆ **6c**) and 505 nm (◆ **7**) (λ_{exc} **5** = 337 nm; λ_{exc} **6a** = 377 nm; λ_{exc} **6b** = 390 nm; λ_{exc} **6c** = 400 nm; λ_{exc} **7** = 405 nm; *T* = 293 K). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

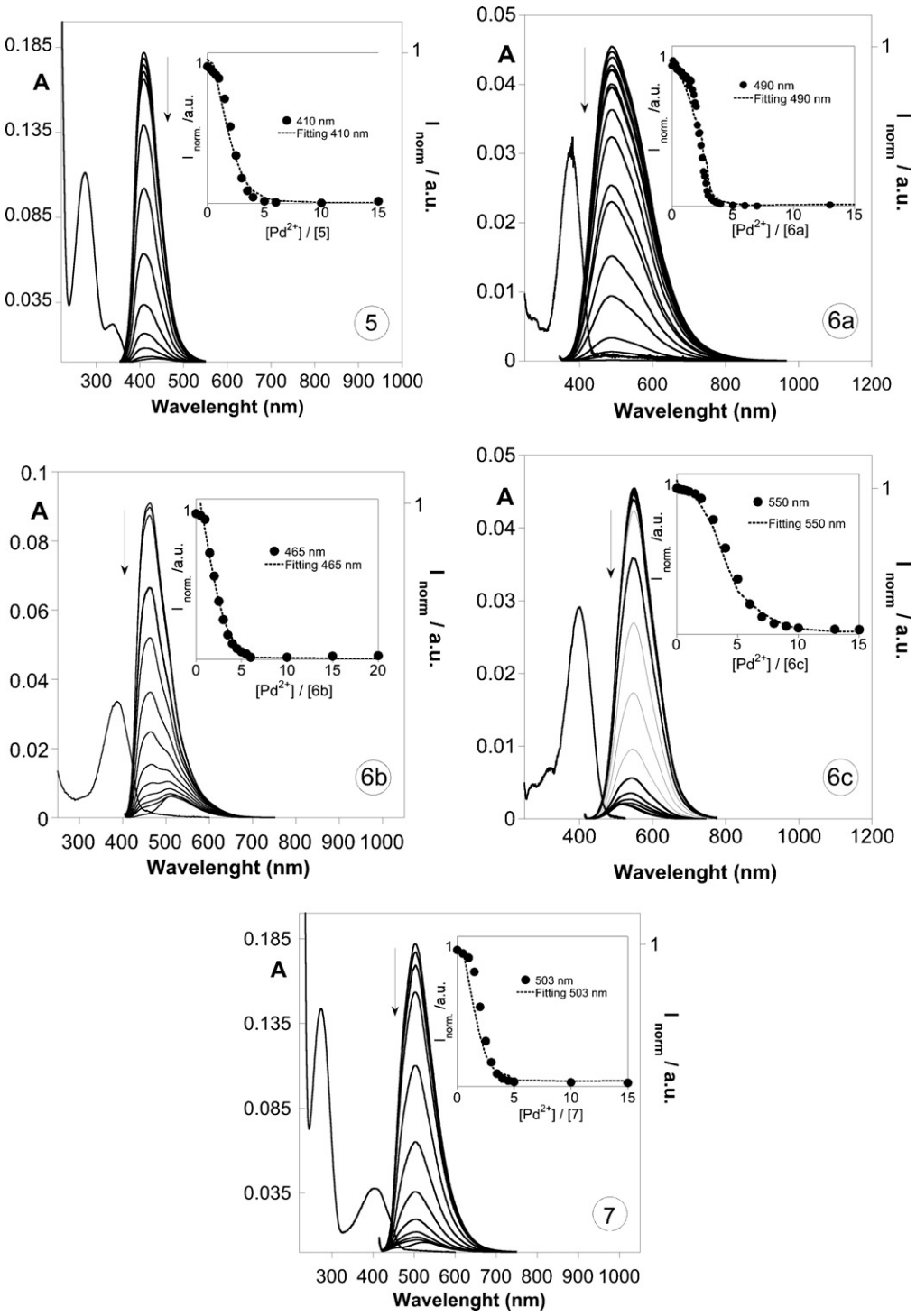


Fig. 3. Absorption and emission spectra of the titration of compounds **5**–**7** with $Pd(CH_3CN)_4(BF_4)_2$ in ACN/DMSO (99:1). Insets: maximum of emission band. (λ_{exc} **5** = 337 nm; λ_{exc} **6a** = 377 nm; λ_{exc} **6b** = 400 nm; λ_{exc} **6c** = 390 nm; λ_{exc} **7** = 405 nm. [5–7] = 1×10^{-6} M; T = 293 K). All calculated curves of fluorescence vs. ion concentration values were fitted using HypSpec program.

The electronic nature of the substituent did not have a marked influence in the fluorescence quantum yields for bithienyl derivatives **6**, which exhibited similar highest values (Φ_F = 0.46–0.57).

3.3. Absorption and emission titration studies

Compounds **5**–**7** are provided with three different binding sites: the NH nitrogen atom of the imidazole heterocycle, a crown ether unit, and sulphur atoms at the thiophene rings. According to the Pearson rules on hard and soft acid-base properties, metals such as Ni^{2+}, Pd^{2+}, Hg^{2+} are considered borderline soft and for this reason they will preferably coordinate to soft donor atoms such as sulphur [17]. Taking this into account, as well as the fact that, depending on the counter ion, 15-crown-5 moieties have a preference for Na^+ cations [8a], modulation of the emission properties can be attained by adding Na^+ before the introduction of soft metals [9c,e].

In order to study the chemosensory behaviour of crown ethers **5**–**7** towards different metal cations (Ni^{2+}, Pd^{2+} and Hg^{2+}) and having in mind our early studies [9c,e], several metal titrations were performed in the presence and in the absence of Na^+. After addition of increasing amount of $NaBF_4$ to different ACN/DMSO (99:1 v/v) solutions of compounds **5**–**7**, the absorption spectrum was very slightly modified: **5** and **6a** showed a blue shift of *ca.* 10 nm after the addition of 500 equivalents of Na^+, while **6b**–**c** and **7** showed a small red-shift of *ca.* 10 nm.

In the emission spectra, the addition of Na^+ to compounds **5**–**7** produced a red shift in the emission band in *ca.* of 20 nm for all ligands, but the fluorescence intensity was practically unaffected (Fig. 2). This result suggests that complexation of Na^+ cations by the crown ethers is too far from the emissive unit to modulate their fluorescence intensity.

Taking into account the presence of O, S and N atoms as donor atoms in the structure of compounds **5**–**7**, titration with Ni^{2+}, Pd^{2+} and Hg^{2+} was carried out. For all compounds, the strongest interaction was observed for Pd^{2+}, with a total quenching of the emission band observed upon addition of 5 equiv. The quenching observed with Pd^{2+} in the case of **6c** was less strong, with 10 equiv. of metal ion being necessary to quench the emission. This fact could be explained probably by the electron-acceptor nature of the cyano group, at the bithienyl system, which could change the coordination capacity of the chelate ring formed by the nitrogen atom of the imidazole ring, and the S atom of the near thiophene ring.

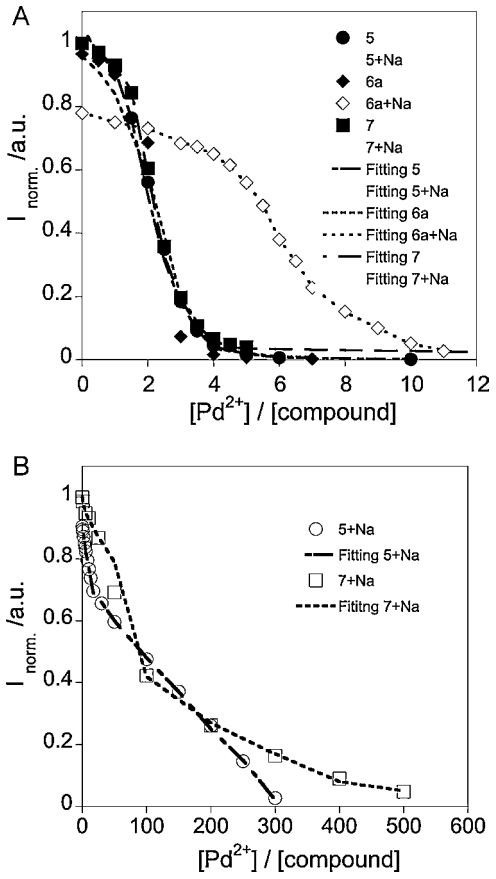


Fig. 4. Titration of compounds **5**, **6a** and **7** with $Pd(CH_3CN)_4(BF_4)_2$ in ACN/DMSO (99:1) (black symbols) and after the addition of 250 equivalents of Na^+ (white symbols). Values taken from the maxima of the emission spectra: 409 nm (**5**), 463 nm (**6a**), 463 nm (**6b**), 540 nm (**6c**) and 505 nm (**7**) (λ_{exc} **5** = 337 nm; λ_{exc} **6a** = 377 nm; λ_{exc} **6b** = 390 nm; λ_{exc} **6c** = 400 nm; λ_{exc} **7** = 405 nm; T = 293 K). Calculated curves of fluorescence vs. ion concentration values were fitted using HypSpec program.

Table 2
Association constants for compounds **5**–**7** in the presence, Pd^{2+}, Na^+, Pd^{2+}, Hg^{2+} and Ni^{2+} in ACN/DMSO (99:1).

Compounds	Metals	log K_{ass} (L:M)
5	Pd^{2+}	12.0 ± 0.01 (1:2)
	Hg^{2+}	5.21 ± 0.02 (1:1)
	Na^+ Pd^{2+}	4.58 ± 0.01 (1:2)
6a	Pd^{2+}	13.24 ± 0.01 (1:2)
	Hg^{2+}	6.10 ± 0.04 (1:1)
	Na^+ Pd^{2+}	9.83 ± 0.03 (1:2)
6b	Pd^{2+}	12.33 ± 0.02 (1:2)
	Hg^{2+}	6.40 ± 0.01 (1:1)
	Na^+ Pd^{2+}	9.32 ± 0.03 (1:2)
	Ni^{2+}	3.71 ± 0.02 (1:1)
6c	Pd^{2+}	10.96 ± 0.01 (1:2)
	Hg^{2+}	6.44 ± 0.01 (1:1)
	Na^+ Pd^{2+}	8.69 ± 0.01 (1:2)
7	Pd^{2+}	12.12 ± 0.01 (1:2)
	Hg^{2+}	9.55 ± 0.01 (1:2)
	Na^+ Pd^{2+}	–

Complexation constants were calculated using the HypSpec program [18] (Table 2). As can be seen, the stronger association constants for Pd^{2+} complexes were obtained with compounds **5** and **6a** and in all cases dinuclear complexes could be postulated.

In Fig. 3 all the fluorescence titrations of compounds **5**–**7** in the presence of increasing amount of $Pd(CH_3CN)_4(BF_4)_2$ in ACN/DMSO (99:1) solutions are shown. As can be observed, the absorption spectra are practically unaffected while the intensity of the fluorescence emission is strongly quenched. This result suggests that the Pd^{2+} interacted directly with the chromophores through the chelate group formed by the imidazo-thiophene unit (NS).

In order to explore the effect of the presence of Na^+ in the transition metal sensing, having in mind the modulation of the sensor behaviour, the same metal titrations were repeated with prior addition of 250 equiv. of $NaBF_4$. The intensity of the quenching observed was notably reduced, suggesting the effect of the ionic strength in the solution and also due to the rigidity imposed by the coordination of the crown ether to Na^+. Therefore, it was necessary to add 12, 300 and more than 500 equiv. of Pd^{2+} to quench the emission of compounds **5**, **6a** and **7**, respectively (Fig. 4A and B). Similar results were obtained for **6b** and **6c**. In conclusion, the coordination of the Pd^{2+} to the NS chelate is less effective when the crown is occupied by Na^+ being carried out by the other binding sites of the molecule. These results are in agreement with the complexation constant obtained in the presence of this metal. For example, for compound **5** the complexation constant changed from log K_{ass} = 12.0 ± 0.01 (L:M = 1:2) to log K_{ass} = 4.58 ± 0.01. A similar behaviour was observed for the other compounds (Table 2).

In the case of the Hg^{2+} titrations, the intensity of the emission band was reduced and also red-shifted (Fig. 5). In general, less metal equivalents where necessary to achieve a similar quenching, when compared to the Pd^{2+} titration, suggesting a stronger interaction with this soft metal ion. In the case of **6b**, both ground and excited state are affected by metal coordination. It is well known that the stronger quenching effect produced by Hg^{2+} coordination on the fluorescence emission of organic chromophores is mainly due to the heavy-atom effect [2f].

In Fig. 5, as general example, are shown the titrations of **5** and **6b** with Hg^{2+} in the absence and in the presence of 250 equiv. of Na^+. As can be observed, the emission band of the compound was quenched and at the same time a new emissive red shifted band was observed with an iso-emissive point. For ligand **6b**, the iso-emissive point appeared at 503 nm and was blue-shifted to 495 nm in the presence of Na^+.

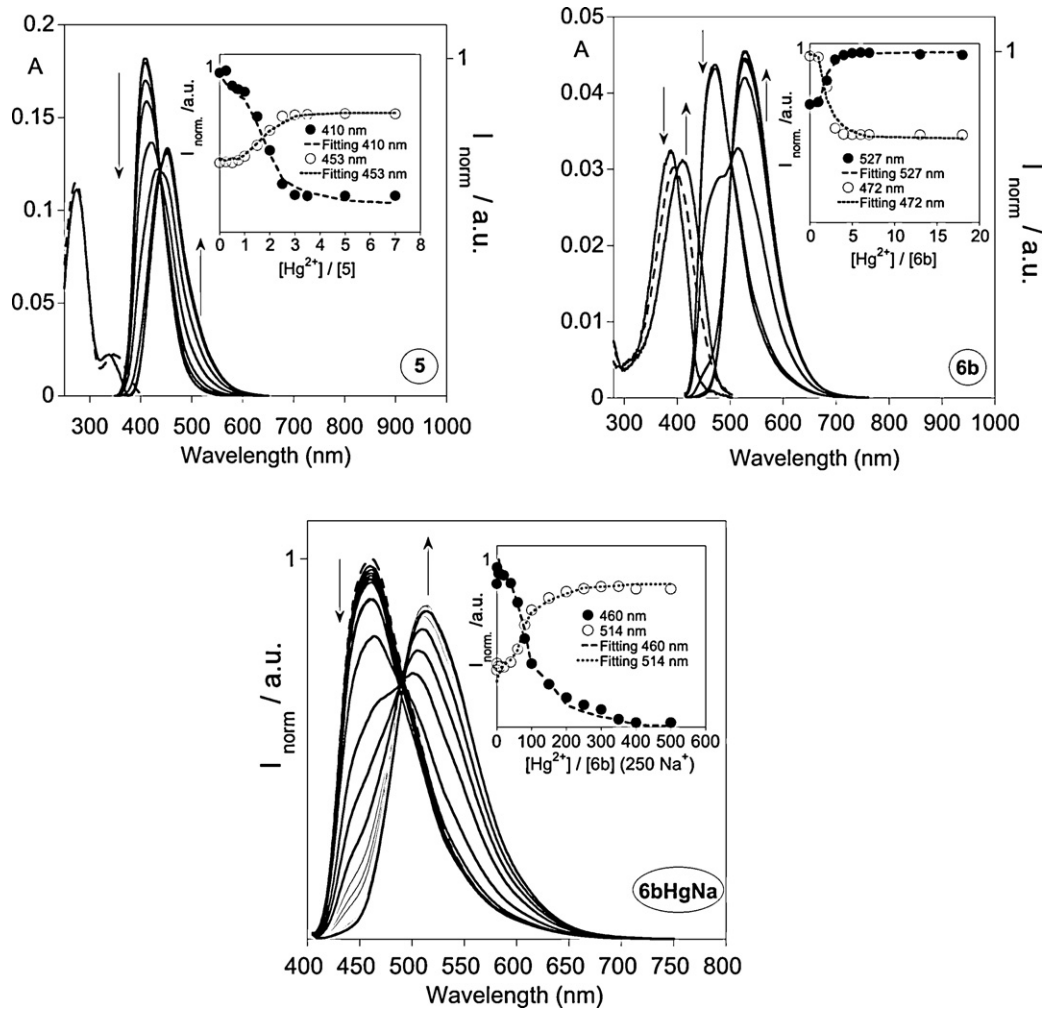


Fig. 5. Absorption spectra of **5** and **6b** after the addition of 4 equivalents of Hg^{2+}, and emission titrations of compounds **5** and **6b** with $Hg(CF_3SO_2)_2(H_2O)_x$ in ACN/DMSO (99:1). In the insets, the values are taken from the emission maxima of the spectra: 410 and 453 nm (**5**); 472 and 527 nm (**6b**); and 460 and 514 nm (**6b**) after the addition of Na^+; (λ_{exc} **5** = 337 nm; λ_{exc} **6b** = 390 nm; T = 293 K). Calculated curves of fluorescence vs. ion concentration values were fitted using HypSpec program.

In order to stabilize this new emissive band in the presence of 250 equiv. of Na^+, the addition of 150 equiv. of Hg^{2+} was necessary. This result is notable, due to the fluorescence enhancement upon chelation (CHEF) effect observed by Hg^{2+} complexation. Most systems using fluorescence spectroscopy for detecting Hg^{2+} are based on the complexation enhancement of the fluorescence quenching (CHEQ) effect [5], and only a few are based on fluorescence enhancement upon chelation (CHEF) effect [6].

As in the previous case of the study with Pd^{2+}, introduction of Na^+ delayed the quenching observed upon heavy metal coordination. This effect can be also explained by a conjunction of the increase of the ionic strength in the medium and the rigidity imposed by the Na^+ coordination of the crown ether. The values of the complexation constants obtained for Hg^{2+} are reported in Table 2. Mononuclear complexes were observed with the exception of compound **7** where probably the introduction of a third thienyl moiety induced the formation of a dinuclear species. A stronger complexation constant was also obtained with this compound ($\log K_{ass}$ 9.55 ± 0.01 and L:M = 1:2).

Absorption and emission titration studies of all compounds **5**-**7** with Ni^{2+} revealed that the interaction produced a small red shift in the absorption band and a quenching in the fluorescence emission less efficient than for the other two metals studied.

In Fig. 6 the fluorescence emission titration upon the addition of increasing amount of Ni^{2+} to **6b** is shown. In this case, it was

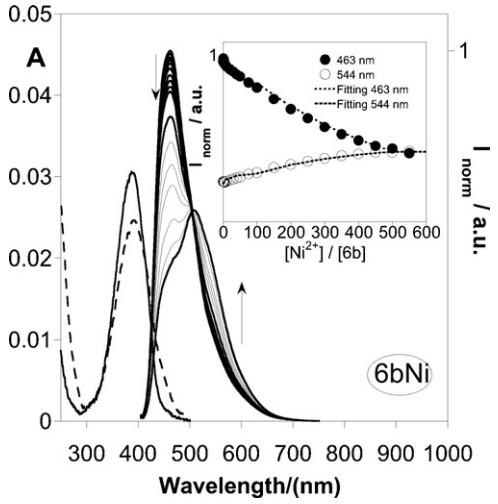


Fig. 6. Titration of **6b** with $Ni(BF_4)_2{\cdot}xH_2O$ in ACN/DMSO (99:1) In the inset: values taken from the maxima of both emission spectra band: 463 and 544 nm (λ_{exc} **6b** = 390 nm; [**6b**] = 1×10^{-6} M; T = 293 K). Calculated curves of fluorescence vs. ion concentration values were fitted using HypSpec program.

necessary to add more than 500 equivalents of metal in order to achieve a plateau at the intensity of the band. As the interaction may take place by the chelate unit imidazo-thienyl NS unit, this effect can be explained having in mind the smaller ionic radius of Ni^{2+} in comparison with Pd^{2+} and Hg^{2+}. In this case the complexation constant gave the smaller value observed ($\log K_{ass} = 3.71 \pm 0.02$). The stoichiometry obtained with Ni^{2+} suggests the formation of a mononuclear complex with compound **6b**.

4. Analytical application

The (oligo)thienyl-imidazo-benzocrown ether receptors could have potential application in analytical chemistry, in the monitoring of various metal cations (Na^+, Ni^{2+}, Pd^{2+} and Hg^{2+}) which exist widely in biological, industrial and environmental processes.

Hg^{2+} and its lipophilic methylmercury derivative and Pd^{2+} are very toxic species and consequently the development of efficient chemosensors for the sensing of these metal ions is one of the most active research fields with great potential for environmental applications.

Detection of palladium species with a fluorescence sensing system is drawing current interest as an easy and sensitive method for determining the palladium contents for example in the drug intermediates synthesized by palladium catalysis or in mining ores, etc. Detection of palladium contents in those samples is usually carried out using analytical tools such as atomic absorption/emission-mass spectrometry, and X-ray fluorescent spectroscopy. These conventional methods, however, require large and expensive instruments as well as sophisticated experimental procedures such as complex sample pretreatments and precautions of cross-contamination from the prior analysis. In contrast, the fluorogenic method can be performed with a fluorimeter through relatively simple analysis protocols [19].

Therefore the study of the limit of detection (LOD) and the limit of quantification (LOQ) for Pd^{2+} was performed for compounds **5**–**7** having in mind their use for real metal-ion detection for analytical applications. In our experimental conditions, at room temperature, in ACN/DMSO (99:1) a LOD of 1.02 ± 0.02 ppm and the LOQ of 1.07 ± 0.08 ppm was determined. For these measurements, ten different analysis for each receptor were performed to obtain the LOQ, and a calibration fit was applied to determine the LOD. The minimum amount of Pd^{2+} that can be quantified was 150, 110, 300, 300 and 285 ppb for **5**, **6a**, **6b**, **6c** and **7**, respectively. Therefore the best candidates for the detection of Pd^{2+} are compounds **5** and **6a**. On the other hand, derivatives functionalized with donor (**6b**, R = MeO) or acceptor groups (**6c**, R = CN) at the bithiophene bridge or introduction of an additional thiophene ring in the bithiophene system (**7**) have reduced sensibility towards Pd^{2+}.

5. Conclusion

In summary, we have prepared through a versatile and simple synthetic method five emissive heterocyclic ligands provided with benzo-15-crown-5 ether units and these receptors were studied as novel metal ion chemosensors. Competition complexation studies in the presence of Na^+ did not modify notably the emission of the systems, but in the presence of this metal ion, the quenching observed after complexation with Ni^{2+}, Pd^{2+}, Hg^{2+} was reduced. This effect could be explained by a conjunction of the increase of the ionic strength in the medium and the rigidity imposed by the coordination of the crown ether to Na^+ ions. A CHEQ effect was observed for all compounds upon coordination of Pd^{2+} and Ni^{2+}, whereas a different behaviour was observed in the presence of Hg^{2+}, in this case the receptors remain emissive upon coordination. The best fluorimetric chemosensors for Pd^{2+} were compounds **5** and **6a**, while compound **7** revealed to be more efficient on the sensing of Hg^{2+}. Moreover, the determination of the LOQ and LOD for Pd^{2+} detection was performed for receptors **5**–**7** showing that the best candidates for the analytical detection of Pd^{2+} are compounds **5** and **6a**.

Acknowledgments

Thanks are due to *Fundação para a Ciência e Tecnologia* (Portugal) for financial support through project PTDC/QUI/66250/2006 (FCOMP-01-0124-FEDER-007428) and PhD grants to R.M.F. Batista (SFRH/BD/36396/2007) and Postdoctoral grant to E. Oliveira (SRFH/BPD/72557/2010). The NMR spectrometer Bruker Avance III 400 is part of the National NMR Network, and was purchased within the framework of the National Program for Scientific Re-equipment, contract REDE/1517/RMN/2005 with funds from POCI 2010 (FEDER) and FCT. C.L. thanks Xunta de Galicia, Spain, for the Isidro Parga Pondal Research Program. We thank to Mr. Tiago Silva for some of the initial metal titrations reported.

References

[1] (a) See for example J.P. Desvergne, A.W. Czarnik (Eds.), Chemosensors of Ion and Molecule Recognition, Kluwer Academic Publishers, Dordrecht, Netherlands, 1997;
(b) B. Valeur, J.-C. Brochon (Eds.), New Trends in Fluorescence Spectroscopy: Applications to Chemical and Life Sciences, Springer, Berlin, 2001;
(c) K. Rurack, U. Resch-Genger, Chem. Soc. Rev. 31 (2002) 116;
(d) Special issue on Luminescent Sensors, Coord. Chem. Rev. (2000) 205.
[2] (a) L. Fabrizzi, A. Poggi, Chem. Soc. Rev. (1995) 197;
(b) A.P. De Silva, H.Q.N. Gunaratne, T. Gunnlaugsson, A.J.M. Huxley, C.P. McCoy, J.T. Rademacher, T.E. Rice, Chem. Rev. 97 (1997) 1515;
(c) L. Prodi, F. Bolletta, M. Montalti, N. Zaccheroni, Coord. Chem. Rev. 205 (2000) 59;
(d) B. Valeur, I. Leray, Coord. Chem. Rev. 205 (2000) 3;
(e) A.P. de Silva, D.B. Fox, A.J.M. Huxley, T.S. Moody, Coord. Chem. Rev. 205 (2000) 41;
(f) K. Rurack, Spectrochim. Acta Part A 57 (2001) 2161;
(g) A.P. De Silva, B. McCaughan, B.O.F. McKinney, M. Querol, Dalton Trans. (2003) 1902;
(h) J.F. Callan, A.P. De Silva, D.C. Magri, Tetrahedron 61 (2005) 8551;
(i) C. Lodeiro, J.L. Capelo, J.C. Mejuto, E. Oliveira, H.M. Santos, B. Pedras, C. Nuñez, Chem. Soc. Rev. 39 (2010) 2948.
[3] (a) X.M. Meng, L. Liu, Q.X. Guo, Progr. Chem. 17 (2005) 45;
(b) W.P. Zhu, Y.F. Xu, X.H. Qian, Progr. Chem. 19 (2007) 1229;
(c) N.E. Okoronkwo, J.C. Igwe, I.J. Okoronkwo, Afr. J. Biotechnol. 6 (2007) 335;
(d) L. Magos, Met. Ions Biol. Syst. 34 (1997) 321;
(e) M.F. Wolfe, S. Schwarzbach, R.A. Sulaiman, Environ. Toxicol. Chem. 17 (1998) 146.
[4] (a) J.M. Benoit, W.F. Fitzgerald, A.W. Damman, Environ. Res. 78 (1998) 118;
(b) H.L. Queen, W.F. Fitzgerald, A.W. Damman, Chronic Mercury Toxicity: New Hope Against An Endemic Disease, Queen and Company Health Communications, Inc, Colorado Springs, 1998;
(c) P. Grandjean, P. Weihe, R.F. White, F. Debes, Environ. Res. 77 (1998) 165;
(d) A. Renzoni, F. Zino, E. Franchi, Environ. Res. 77 (1998) 68;
D.W. Boening, Chemosphere 40 (2000) 1335;
(e) E. Guallar, M.I. Sanz-Gallardo, P.V. Veer, P. Bode, A. Aro, J. Gómez-Aracena, J.D. Kark, R.A. Riemersma, J.M. Martín-Moreno, F.J. Kok, N. Engl. J. Med. 347 (2002) 1747;
(f) T.W. Clarkson, L. Magos, G.J. Meyrs, N. Engl. J. Med. 349 (2003) 1731;
(g) A.H. Stern, R.J.M. Hudson, C.W. Shade, S. Ekino, T. Ninomiya, M. Susa, H.H. Harris, I.J. Pickering, G.N. George, Science 303 (2004) 763.
[5] (a) E.M. Nolan, S.J. Lippard, Chem. Rev. 108 (2008) 3443;
(b) A. Tamayo, B. Pedras, C. Lodeiro, L. Escriche, J. Casabó, J.L. Capelo, B. Covelo, R. Kivekas, R. Sillanpaa, Inorg. Chem. 46 (2007) 7818;
(c) M. Mameli, V. Lippolis, J.L. Capelo, O. Nieto-Faza, C. Lodeiro, Inorg. Chem. 49 (2010) 8276.
[6] (a) Y.K. Yang, K.J. Yook, J. Tae, J. Am. Chem. Soc. 127 (2005) 16760;
(b) G. Zhang, D. Zhang, S. Yin, X. Yang, Z. Shuai, D. Zhu, Chem. Commun. 16 (2005) 2161;
(c) X. Guo, X. Qian, L. Jia, J. Am. Chem. Soc. 126 (2004) 2272;
(d) E.M. Nolan, S.J. Lippard, J. Am. Chem. Soc. 125 (2003) 14270;
(e) G. Hennrich, W. Walther, U. Resch-Genger, H. Sonnenshein, Inorg. Chem. 40 (2001) 641;
(f) Y. Zhao, Z. Lin, C. He, H. Wu, C. Duan, Inorg. Chem. 45 (2006) 10013.
[7] (a) J. Le Bars, U. Specht, J.S. Bradley, D.G. Blackmond, Langmuir 15 (1999) 7621;
(b) T. Iwasawa, M. Tokunaga, Y. Obora, Y. Tsuji, J. Am. Chem. Soc. 126 (2004) 6554;
(c) M. Lafrance, K. Fagnou, J. Am. Chem. Soc. 128 (2006) 16496;
(d) V.F. Hodge, M.O. Stallard, Environ. Sci. Technol. 20 (1986) 1058;

(e) G. Zeni, R.C. Larock, Chem. Rev. 104 (2004) 2285;
(f) L.F. Tietze, H. Ila, H.P. Bell, Chem. Rev. 104 (2004) 3453;
(g) K.C. Nicolaou, P.G. Bulger, D. Sarlah, Angew. Chem. Int. Ed. 44 (2005) 4442;
(h) X. Chen, K.M. Engle, D.H. Wang, J.Q. Yu, Angew. Chem. Int. Ed. 48 (2009) 5094;
(i) International Programme on Chemical Safety. Palladium, Environmental Health Criteria Series 226, World Health Organization, Geneva, 2002;
(j) C.E. Garrett, K. Prasad, Adv. Synth. Catal. 346 (2004) 889;
(k) B. Dimitrova, K. Benkhedda, E. Ivanova, F. Adams, J. Anal. At. Spectrom. 19 (2004) 1394;
(l) C. Locatelli, D. Melucci, G. Torsi, Anal. Bioanal. Chem. 382 (2005) 1567;
(m) K. Van Meel, A. Smekens, M. Behets, P. Kazandjian, R. Van Grieken, Anal. Chem. 79 (2007) 6383;
(n) L.P. Duan, Y.F. Xu, X.H. Qian, Chem. Commun. (2008) 6339;
(o) Q.E. Cao, Y.K. Zhao, X.J. Yao, Z.D. Hu, Q.H. Xu, Spectrochim. Acta A 56 (2000) 1319;
(p) A. Tamayo, L. Escriche, J. Casabó, B. Covelo, C. Lodeiro, Eur. J. Inorg. Chem. (2006) 2997;
(q) G.H. Zhu, Z.C. Zhu, X. Hun, Y.L. Chen, Chin. J. Anal. Chem. 31 (2006) 48;
(r) T. Schwarze, H. Muller, C. Dosche, T. Klamroth, W. Mickler, A. Kelling, H.G. Lohmannsroben, P. Saalfrank, H.J. Holdt, Angew. Chem. Int. Ed. 46 (2007) 1671.

[8] (a) G.W. Gokel, W.M. Leevy, M.E. Weber, Chem. Rev. 104 (2004) 2723;
(b) S. Fery-Forgues, F. Al-Ali, J. Photochem. Photobiol. C: Photochem. Rev. 5 (2004) 139;
(c) E. Karapinar, E. Özcan, J. Inclusion Phenom. Macroc. Chem. 47 (2003) 59;
(d) J.-E. Jee, M.C. Chang, C.-H. Kwak, Inorg. Chem. Commun. 7 (2004) 614;
(e) K.M.C. Wong, W.-P. Li, K.K.-K. Cheung, V.W.-W. Yam, New J. Chem. 29 (2005) 165;
(f) J. Arias, M. Bardají, P. Espinet, J. Organomet. Chem. 691 (2006) 4990.

[9] (a) R.M.F. Batista, E. Oliveira, S.P.G. Costa, C. Lodeiro, M.M.M. Raposo, Org. Lett. 9 (2007) 3201;
(b) S.P.G. Costa, E. Oliveira, C. Lodeiro, M.M.M. Raposo, Sensors 7 (2007) 2096;
(c) R.M.F. Batista, E. Oliveira, S.P.G. Costa, C. Lodeiro, M.M.M. Raposo, Tetrahedron Lett. 49 (2008) 6575;
(d) R.M.F. Batista, E. Oliveira, C. Nuñez, S.P.G. Costa, C. Lodeiro, M.M.M. Raposo, J. Phys. Org. Chem. 22 (2009) 362;
(e) B. Pedras, L. Fernandes, E. Oliveira, L. Rodriguez, M.M.M. Raposo, J.L. Capelo, C. Lodeiro, Inorg. Chem. Commun. 12 (2009) 79;
(f) M.M.M. Raposo, B. García-Acosta, T. Ábalos, R. Martínez-Manez, J.V. Ros-Lis, J. Soto, J. Org. Chem. 75 (2010) 2922;
(g) C.I.C. Esteves, M.M.M. Raposo, S.P.G. Costa, Tetrahedron 66 (2010) 7479;
(h) C.I.C. Esteves, M.M.M. Raposo, S.P.G. Costa, Amino Acids 40 (2011) 1065;
(i) E. Oliveira, R.M.F. Batista, S.P.G. Costa, C. Lodeiro, M.M.M. Raposo, Inorg. Chem. 49 (2010) 10847, 49;
(j) E. Oliveira, S.P.G. Costa, M.M.M. Raposo, O.N. Faza, C. Lodeiro, Inorg. Chem. Acta 366 (2011) 154.

[10] M.M.M. Raposo, A.M.C. Fonseca, G. Kirsch, Tetrahedron 59 (2003) 4891.

[11] R.M.F. Batista, S.P.G. Costa, M. Belsley, C. Lodeiro, M.M.M. Raposo, Tetrahedron 64 (2008) 9230.

[12] D.D. Perrin, W.L.F. Armarego, Purification of Laboratory Chemicals, 3rd ed., Pergamon, Oxford, 1988.

[13] (a) I.B. Berlan, Handbook of Fluorescence Spectra of Aromatic Molecules, 2nd ed., Academic Press, New York, 1971;
(b) W.H. Melhuish, J. Phys. Chem. 84 (1961) 229.

[14] (a) D. Yang, D. Fokas, J. Li, L. Yu, C.M. Baldino, Synthesis 1 (2005) 47;
(b) R.M.F. Batista, S.P.G. Costa, M. Belsley, M.M.M. Raposo, Tetrahedron 63 (2007) 9842.

[15] (a) S.P.G. Costa, E. Oliveira, C. Lodeiro, M.M.M. Raposo, Tetrahedron Lett. 49 (2008) 5258;
(b) S.P.G. Costa, R.M.F. Batista, M.M.M. Raposo, Tetrahedron 64 (2008) 9733.

[16] (a) R.S. Becker, J. Seixas de Melo, A.L. Maçanita, F. Elisei, J. Phys. Chem. 100 (1996) 18683;
(b) J. Seixas de Melo, L.M. Silva, L.G. Arnaut, R.S. Becker, J. Chem. Phys. 111 (1999) 5427;
(c) S. Dufresne, M. Bourgeaux, W.G. Skene, J. Mater. Chem. 17 (2007) 1166;
(d) J. Seixas de Melo, H.D. Burrows, M. Svensson, M.R. Andreson, A.P.J. Monkman, Chem. Phys. 11 (2003) 1550.

[17] R.G.J. Pearson, Am. Chem. Soc. 85 (1963) 3533.

[18] P. Gans, A. Sabatini, A. Vacca, Talanta 43 (1996) 1739.

[19] (a) K. Van Meel, A. Smekens, M. Behets, P. Kazandijian, R. Van Grieken, Anal. Chem. 79 (2007) 6383;
(b) C. Locatelli, D. Melucci, G. Torsi, Anal. Bioanal. Chem. 382 (2005) 1567;
(c) B. Dimitrova, K. Benkhedda, E. Ivanova, F. Adams, J. Anal. Spectrom. 19 (2004) 1394.