

Synthesis and evaluation of arylfuryl-*bis*(indolyl)methanes as selective chromogenic and fluorogenic ratiometric receptors for mercury ion in aqueous solution

Rosa M. F. Batista, Susana P. G. Costa, Regina M. P. Silva, Nuno E. M. Lima, M. Manuela M. Raposo*

Centre of Chemistry, University of Minho, Campus of Gualtar, 4710-057 Braga, Portugal

*Corresponding author Tel: + 351 253 604381; Fax: + 351 253 604382
email: mfox@quimica.uminho.pt

Abstract- A series of arylfuryl-*bis*(indolyl)methane derivatives **2** were prepared in good yields by electrophilic substitution of indole with furyl aldehydes through a simple and mild hydrogensulfate-catalyzed reaction and studied as chemosensors for transition metal cations by performing spectrophotometric and spectrofluorimetric titrations. Selective recognition of Hg²⁺ was achieved in organic aqueous mixture (CH₃CN/H₂O, 7:3) for the various receptors, with an easily detectable colour change from colourless to purple and also through a fluorescence quenching, making these compounds suitable for dual chromo- and ratiometric fluorogenic sensing of Hg²⁺. The binding stoichiometry between the receptors and Hg²⁺ was found to be 1:1. The binding process was also followed by ¹H NMR titrations which corroborated the previous findings.

Keywords: *Bis*(indolyl)methanes; arylfuran; ratiometric fluorogenic chemosensors; Hg²⁺; direct visual detection; aqueous solution.

1. Introduction

Chemosensors and chemodosimeters that can monitor heavy metal ions with high sensitivity and selectivity are especially important owing to the great concern with environment and health. Among transition and heavy metals, mercury, from a variety of natural and anthropogenic sources and widely distributed in water, soil and air, is

considered to be one of the most toxic because both ionic and elemental mercury can be converted by bacteria in the environment to methyl mercury, which subsequently bioaccumulates through the food chain. Mercury causes serious neurotoxic, genotoxic, and immunotoxic effects and thus poses severe risk for human beings and other organisms. Therefore, selective and sensitive detection of Hg^{2+} has been an important topic of investigation [1]. Presently, several methods such as atomic absorption/emission spectroscopy, inductively coupled plasma-mass spectrometry, voltammetry, etc. can be used in order to detect Hg^{2+} . However, all these methods have drawbacks such as expensive instrumentation, only measure the total metal ion content and are not suitable for on-site assays [2]. Therefore, an easy and straightforward method that detects and quantifies Hg^{2+} is advantageous for instantaneous monitoring of environmental, biological, and industrial samples which occur in aqueous solution. Consequently, much attention has been paid to developing low-cost and easily-prepared colorimetric and/or fluorimetric mercury sensors that work in the aqueous medium [1a-b,d-f,h-m]. Hg^{2+} is usually associated with a fluorescence quenching by different mechanisms, so a ratiometric approach for its detection (simultaneous monitoring of fluorescence intensity at two different wavelengths) would be preferable, since it minimizes interferences from other species present in the media [1b,i,l].

Although indoles are predominant in natural compounds and widely applied in the synthesis of pharmaceutical products, they were only recently recognized as useful building blocks for the assembly of synthetic anionic receptors [3]. Among the several indole-based systems, triaryl- and triheteroarylmethanes have found wide range applications in different areas of chemistry, due to their structure (presence of a pyrrolic NH group) and photophysical properties, such as chemical sensors [3-5] and as precursors in the synthesis of heterocyclic systems for molecular electronics [6]. Therefore, there is a great deal of interest in the synthesis of this class of compounds and while several indole-based receptors have been developed for the selective sensing and detection of anions [3-5] only a few examples can be found in the literature for cation receptors bearing an indole group [7].

Recently, the synthesis and evaluation of new *bis*-indolylmethenes containing thienyl and bithienyl moieties has been reported by us in order to evaluate the effect of the length of the π -conjugated bridge and also the electronic nature of these heterocycles on the sensory properties of these chromophores [8]. Keeping in mind our interests in the synthesis of colorimetric/fluorimetric chemosensors for selective detection of

cations and anions, we proceeded to synthesize new non-oxidized *bis*-indolylmethane derivatives containing functionalized arylfuryl moieties and evaluate their chemosensory ability. The main difference resides in the replacement of the π -conjugated bi(thiophene) spacer by an arylfuryl system (instead of the more commonly used aryl group), allowing a more sensitive fluorimetric detection due to the higher fluorescent character of the heteroaromatic furan when compared to thiophene [9]. On the other hand, the different electronic nature of the substituents at the arylfuryl group was used to tune the photophysical properties of the resulting compounds. These non-conjugated *bis*-indolylmethane derivatives with an sp^3 carbon at *meso* position may even promote more significant color changes when compared with the previous examples, probably because the interaction with cations can occur through a variation in carbon hybridization with concomitant modulation of the internal charge transfer (ICT) state.

2. Experimental

2.1. Synthesis general

Reaction progress was monitored by thin layer chromatography (0.25 mm thick precoated silica plates: Merck Fertigplatten Kieselgel 60 F254), while purification was effected by silica gel column chromatography (Merck Kieselgel 60; 230-400 mesh). 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. Fluorescence spectra were collected using a FluoroMax-4 spectrofluorometer. UV-visible absorption spectra (200 – 700 nm) were obtained using a Shimadzu UV/2501PC spectrophotometer. Luminescence quantum yields were measured using quinine sulphate in 0.5 M sulphuric acid solution as standard ($\phi_F=0.54$) [10]. All commercially available reagents were used as received.

2.2. Synthesis of 5-(4'-methoxyphenyl)furan-2-carbaldehyde (**1b**)

5-Bromofuran-2-carbaldehyde (1.5 mmol) was coupled with 4-methoxyphenylboronic acid (1.9 mmol) in a mixture of DME (15 mL), aqueous 2 M Na₂CO₃ (1 mL) and Pd(PPh₃)₄ (6 mol %) at 80 °C under argon. The reaction was monitored by TLC and after cooling, the mixture was filtered. Ethyl acetate and a saturated solution of NaCl were added and the phases were separated. The organic phase was washed with water (3×50 mL) and with a solution of NaOH (10%) (1×50 mL). The organic phase obtained was dried (MgSO₄), filtered and the solvent removed to give a crude mixture. The crude residue was submitted to silica gel column chromatography using mixtures of hexane and chloroform of increasing polarity. The fractions containing the purified product were collected and evaporated under vacuum to afford product **1b** as orange oil (82%). IR (liquid film): $\nu = 1667, 1590, 1500, 1213, 1176, 1112, 1066, 1020, 965, 830, 767 \text{ cm}^{-1}$. ¹H NMR (CDCl₃): $\delta = 3.86$ (s, 3H, OCH₃), 6.96 (dd, 2H, $J = 9.0$ and 2.1 Hz, H3' and H5'), 7.29 (d, 1H, $J = 3.9$ Hz, H4), 7.62 (dd, 2H, $J = 9.0$ and 2.1 Hz, H2' and H6'), 7.71 (d, 1H, $J = 3.9$ Hz, H3), 9.86 (s, 1H, CHO) ppm.

2.3. General procedure for the synthesis of bis(indolyl)methanes **2a-d**

KHSO₄ (1.20 mmol) was added to a mixture of indole (2.40 mmol) and the corresponding aldehyde **1a-d** (1.20 mmol) in dry methanol (10 mL), and the reaction was stirred at room temperature for 7 h. Then water (10 mL) was added to quench the reaction, and the aqueous phase was extracted with CHCl₃ (3 x 20 mL). The organic phase was dried with anhydrous MgSO₄, and the crude compounds **2** were purified by recrystallization from CHCl₃.

2.3.1. 3-((1H-Indol-3-yl)(5'-phenylfuran-2'-yl)methyl)-1H-indole (**2a**).

Pink solid (50 %). Mp: 192.0-193.0 °C. IR (Nujol) $\nu = 3412, 3055, 2955, 2925, 1610, 1594, 1544, 1419, 1336, 1214, 1203, 1090, 1018, 789, 763, 745 \text{ cm}^{-1}$. ¹H NMR (acetone-*d*₆) $\delta = 6.09$ (s, 1H, CH), 6.23 (d, 1H, $J = 3.3$ Hz, H3'), 6.79 (d, 1H, $J = 3.3$ Hz, H4'), 6.98 (dt, 2H, $J = 7.6$ and 1.4 Hz, 2 x H5), 7.11 (dt, 2H, $J = 7.6$ and 1.4 Hz, 2 x H6), 7.17 (d, 2H, $J = 2.1$ Hz, 2 x H2), 7.24 (m, 1H, H4''), 7.38-7.42 (m, 2H, H3'' and H5''), 7.44 (dt, 2H, $J = 7.5$ and 1.4 Hz, 2 x H7), 7.59 (d, 2H, $J = 7.5$ Hz, 2 x H4), 7.68

(d, 2H, $J = 8.3$ Hz, H2'' and H6''), 10.11 (s, 2H, 2 x NH). ^{13}C NMR (acetone- d_6) $\delta = 35.2$ (CH), 106.7 (C4'), 109.2 (C3'), 112.2 (2 x C7), 117.2 (2 x C3), 119.4 (2 x C5), 120.2 (2 x C4), 122.1 (2 x C6), 124.0 (C2'' and C6''), 124.2 (2 x C2), 127.6 (C4''), 127.8 (2 x C3a), 129.5 (C3'' and C5''), 132.2 (C1''), 137.9 (2 x C7a), 153.0 (C5'), 158.8 (C2'). MS (EI) m/z (%): 388 (M^+ , 42), 283 (100), 273 (23), 168 (20), 117 (21), 77 (13). HRMS: (EI) m/z (%) for $\text{C}_{27}\text{H}_{20}\text{N}_2\text{O}$; calcd 388.1576; found 388.1577.

2.3.2. 3-((1H-Indol-3-yl)(5'-(4''-methoxyphenyl)furan-2'-yl)methyl)-1H-indole (2b).

Purple solid (40 %). Mp: 115.0-116.0 °C. IR (Nujol) $\nu = 3411, 2920, 1616, 1598, 1547, 1498, 1420, 1295, 1249, 1176, 1094, 1021, 967, 832, 782, 743$ cm^{-1} . ^1H NMR (acetone- d_6) $\delta = 3.82$ (s, 3H, OCH_3), 6.06 (s, 1H, CH), 6.18 (d, 1H, $J = 3.3$ Hz, H3'), 6.61 (d, 1H, $J = 3.3$ Hz, H4'), 6.94-7.00 (m, 4H, H3'', H5'' and 2 x H5), 7.10 (dt, 2H, $J = 7.8$ Hz, 2 x H6), 7.15 (d, 2H, $J = 2.4$ Hz, 2 x H2), 7.42 (d, 2H, $J = 7.8$ Hz, 2 x H7), 7.57-7.63 (m, 4H, H2'', H6'' and 2 x H4), 10.10 (s, 2H, 2 x NH). ^{13}C NMR (acetone- d_6) $\delta = 35.2$ (CH), 55.5 (OCH_3), 104.9 (C4'), 109.0 (C3'), 112.2 (2 x C7), 114.9 (C3'' and C5''), 117.4 (2 x C3), 119.4 (2 x C5), 120.2 (2 x C4), 122.0 (2 x C6), 124.2 (2 x C2), 125.2 (C1''), 125.5 (C2'' and C6''), 127.8 (2 x C3a), 137.9 (2 x C7a), 153.2 (C5'), 157.9 (C2'), 159.8 (C4''). MS (EI) m/z (%): 418 (M^+ , 37), 303 (27), 283 (100), 168 (13), 135 (18), 117 (21). HRMS: (EI) m/z (%) for $\text{C}_{28}\text{H}_{22}\text{N}_2\text{O}_2$; calcd 418.1681; found 418.1682.

2.3.3. 3-((5'-(4''-Bromophenyl)furan-2'-yl)(1H-indol-3-yl)methyl)-1H-indole (2c).

Pale pink solid (54 %). Mp: 116.0 -117.0 °C. IR (Nujol) $\nu = 3409, 2919, 1538, 1477, 1418, 1338, 1242, 1205, 1094, 1073, 1008, 967, 826, 783, 743$ cm^{-1} . ^1H NMR (acetone- d_6) $\delta = 6.08$ (s, 1H, CH), 6.25 (d, 1H, $J = 3.2$ Hz, H3'), 6.85 (d, 1H, $J = 3.2$ Hz, H4'), 6.97 (t, 2H, $J = 7.2$ Hz, 2 x H5), 7.10 (t, 2H, $J = 7.2$ Hz, 2 x H6), 7.16 (d, 2H, $J = 1.6$ Hz, 2 x H2), 7.42 (d, 2H, $J = 8.4$ Hz, 2 x H7), 7.54-7.63 (m, 6H, H2'', H3'', H5'', H6'' and 2 x H4), 10.10 (s, 2H, 2 x NH). ^{13}C NMR (CDCl_3) $\delta = 34.3$ (CH), 106.4 (C4'), 109.0 (C3'), 111.1 (2 x C7), 116.9 (2 x C3), 119.4 (2 x C5), 119.7 (2 x C4), 120.4 (C4''), 121.9 (2 x C6), 123.1 (2 x C2), 124.9 (C2'' and C6''), 126.7 (2 x C3a), 130.1 (C1''), 131.6 (C3'' and C5''), 136.5 (2 x C7a), 151.5 (C5), 157.3 (C2'). MS (ESI) m/z (%): 467 ($\text{M} + ^{81}\text{Br}$, 35), 465 ($\text{M} + ^{79}\text{Br}$, 35), 431 (28), 367 (28), 345 (66), 289 (14), 231 (49), 227 (100), 187 (30), 159 (16). HRMS: (ESI) m/z (%) for $\text{C}_{27}\text{H}_{18}^{81}\text{BrN}_2\text{O}$ calcd 467.05779; found 467.05753. $\text{C}_{27}\text{H}_{18}^{79}\text{BrN}_2\text{O}$; calcd 465.05970; found 465.05900.

2.3.4. 3-((1*H*-Indol-3-yl)(5'-(4''-nitrophenyl)furan-2'-yl)methyl)-1*H*-indole (**2d**).

Yellow solid (65%). Mp: 119.0-120.0 °C. IR (Nujol) ν = 3409, 2925, 1602, 1536, 1507, 1335, 1109, 1096, 1057, 1022, 968, 852, 783, 742, 722 cm^{-1} . ^1H NMR (acetone- d_6) δ = 6.14 (s, 1H, CH), 6.36 (d, 1H, J = 4.4 Hz, H3'), 6.99 (dt, 2H, J = 7.2 and 0.8 Hz, 2 x H5), 7.09-7.15 (m, 3H, 2 x H6 and H4'), 7.19 (d, 2H, J = 2.4 Hz, 2 x H2), 7.44 (d, 2H, J = 8.5 Hz, 2 x H7), 7.20 (d, 2H, J = 8.5 Hz, 2 x H4), 7.91 (dd, 2H, J = 7.2 and 2.0 Hz, H2'' and H6''), 8.25 (dd, 2H, J = 7.2 and 2.0 Hz, H3'' and H5''), 10.15 (s, 2H, 2 x NH). ^{13}C NMR (acetone- d_6) δ = 35.3 (CH), 110.3 (C3'), 111.5 (C4'), 112.3 (2 x C7), 116.7 (2 x C3), 119.5 (2 x C5), 120.1 (2 x C4), 122.2 (2 x C6), 124.3 (2 x C2), 124.4 (C2'' and C6''), 125.1 (C3'' and C5''), 127.7 (2 x C3a), 137.7 (C1''), 137.9 (2 x C7a), 146.9 (C4''), 151.1 (C5'), 161.5 (C2'). MS (EI) m/z (%): 456 (M^+ , 19), 432 (58), 359 (25), 313 (42), 245 (100), 218 (72), 179 (23). HRMS: (EI) m/z (%) for $\text{C}_{27}\text{H}_{19}\text{N}_3\text{NaO}_3$; calcd 456.13186; found 456.13041.

2.4. Spectrophotometric and spectrofluorimetric titrations of compounds **2a-d**

Solutions of *bis*-(indolyl)methane derivatives **2a-d** (ca. 1.0×10^{-5} to 1.0×10^{-6} M) and of the cations under study (ca. 1.0×10^{-1} to 1.0×10^{-3} M) were prepared in MeCN/ H_2O (7:3) (in the form of hexahydrated tetrafluoroborate salts for Cu^{2+} , Co^{2+} , Ni^{2+} , Pd^{2+} , and perchlorate salts for Cd^{2+} , Ca^{2+} , Na^+ , Cr^{3+} , Zn^{2+} , Hg^{2+} , Fe^{2+} and Fe^{3+}). Titration of the compounds was performed by the sequential addition of a metal cation to the *bis*-(indolyl)methane derivative solution, in a 10 mm path length quartz cuvette and emission spectra were measured by excitation at the wavelength of maximum absorption for each compound, indicated in Table 1. The binding stoichiometry of the *bis*-(indolyl)methane derivatives with the metal cations was determined by using Job's plots, by varying the molar fraction of the cation while maintaining constant the total *bis*-(indolyl)methane derivative and metal cation concentration. The association constants were obtained from Hyperquad Software.

2. Results and discussion

2.1. Synthesis and characterization

A new series of arylfuryl-*bis*(indolyl)methanes **2** was synthesized with substituents such as alkoxy, bromo or nitro, in order to evaluate the influence of the electron

donating or withdrawing strength of the substituent groups on the optical and sensing properties of the receptors. These compounds were obtained in moderate to good yields (40-65%) by condensation of indole with several formyl precursors **1** with substituents of different electronic nature in dry methanol in the presence of potassium hydrogensulfate [11] (Scheme 1). Formyl-arylfuran precursors **1a** and **1c-d** were commercially available and 5-(4'-methoxyphenyl)furan-2-carbaldehyde **1b** [12] was synthesized by us through Suzuki cross-coupling reaction [13].

<Scheme 1>

These new systems constituted by aryl-furan π -conjugated bridges displayed an increased intramolecular charge transfer due to the high electronegativity of the oxygen at the heteroaromatic ring. As a consequence, the acidity of the indolyl NH was increased, with a bathochromic shift in absorption and emission bands and quite pronounced color changes. In compound **2b** the electron donor methoxy group induced a certain decrease in the acidity of the NH proton ($\delta = 10.10$ ppm) when compared to the arylfuryl-*bis*(indolyl)methane functionalized with a nitro group (compound **2d**, $\delta = 10.15$ ppm). A dramatic bathochromic shift from 289 nm to 370 nm was observed for compound **2d**, when compared with compound **2b**, being a direct consequence of the electronic nature of the substituent at the arylfuran moiety. The high fluorescence of the furan ring also gave these new systems the advantage of using a more sensitive technique to detect metal cations. The relative fluorescence quantum yields were determined using a 10^{-6} M solution of quinine sulfate in 0.5 M H_2SO_4 as standard ($\phi_F=0.54$) [10]. The absorption and emission spectra of arylfuryl-*bis*(indolyl)methanes **2** were measured in MeCN/ H_2O (7:3) solution (10^{-6} to 10^{-5} M solution) (Table 1). Arylfuryl-*bis*(indolyl)methanes **2** exhibited different fluorescence quantum yields according to the functionalization at the furan ring: higher ϕ_F for the hydrogen and methoxy groups (0.21 and 0.58, respectively for compounds **2a-b**), and low fluorescence in the case of compounds **2c-d** with bromine and nitro groups (ϕ_F 0.01 and 0.001, respectively). Considering these photophysical properties, derivatives **2a-b** would be the more interesting candidates as chemosensors due to the higher fluorescence quantum yields, important for maximization of the response in the analysis of very dilute samples.

<Figure 1>

<Table 1>

2.2 Spectrophotometric/spectrofluorimetric titrations and chemosensing studies of 2a-d with metallic cations

Compounds **2a-d** were evaluated as chemosensors in the presence of several metal cations (Cu^{2+} , Co^{2+} , Ni^{2+} , Pd^{2+} , Cd^{2+} , Ca^{2+} , Cr^{3+} , Zn^{2+} , Hg^{2+} , Fe^{2+} and Fe^{3+}) in MeCN/ H_2O (7:3) solutions. The hexahydrated tetrafluoroborate salts of Cu^{2+} , Co^{2+} , Ni^{2+} and Pd^{2+} and perchlorate salts of Cd^{2+} , Ca^{2+} , Cr^{3+} , Zn^{2+} , Hg^{2+} , Fe^{2+} and Fe^{3+} were added to solutions of **2a-d** (10^{-4} M), in order to evaluate their chemosensory ability. A preliminary study with 100 equiv of the cations revealed that compounds **2a-d** responded selectively to the presence of Hg^{2+} with a distinct color change from colorless to purple (Figure 2).

<Figure 2>

Regarding the fluorimetric response, selectivity towards Hg^{2+} was also achieved with a clearly visible quenching in the fluorescence intensity, (Figure 3), that can be attributed to electron and/or energy transfer processes due to empty d shell of Hg^{2+} [7c].

<Figure 3>

Spectrophotometric titration of compounds **2a-b, d** in MeCN/ H_2O (7:3) (10^{-5} - 10^{-6} M) with Hg^{2+} revealed a trend in the UV-vis spectra: the intensity of the longest wavelength absorption band (between 290-377 nm) decreased progressively upon addition of the metal cation, with the simultaneous growth of a new red-shifted absorption band located between 505-543 nm. On the other hand, for compound **2c** there was a very slight increase of the corresponding absorption band at 267 nm together with the appearance of a new band at 518 nm of low intensity (Figure 4). The number of necessary metal equivalents to achieve a plateau was between 30-40 equivalents for compounds **2a-c** and at about 100 equivalents for compound **2d**.

<Figure 4>

In order to gain insight into the interaction mechanism between the cation and the receptors, similar titrations with Hg^{2+} were also conducted in MeCN/ H_2O at different pH (2.05 and 7.05). In both cases there was no formation of the red-shifted band upon addition of the metal, revealing that no interaction took place due to the fact that the indolyl NH was protonated.

The association constants (K_{ass}), the detection (LOD) and quantification (LOQ) limits were also obtained from the results of the spectrophotometric titrations in MeCN/ H_2O (7:3) (Table 2). The highest association constant was found for compound **2b** bearing the electron donor methoxy group linked to the arylfuryl moiety.

<Table 2>

The stoichiometry of the complexes was obtained by the changes in the colorimetric response of compounds **2a-d** in the presence of varying concentrations of Hg^{2+} (Figure 5). The results indicated an empirical 1:1 ratio (L:M), which is also in agreement with the stoichiometry suggested from Hyperquad Software.

<Figure 5>

As for the spectrofluorimetric titrations in MeCN/ H_2O (7:3), only compounds **2a-b** were studied since the other compounds were not fluorescent. The response to the presence of Hg^{2+} was seen by a variation in the fluorescence intensity of the emission band (Figure 5), after excitation at the maximum wavelength of absorption of the ligand and of the complex between the metal and the ligand. The results are similar for both compounds, with a quenching of fluorescence being visible for the ligand emission band, whereas the opposite effect occurred with an increase of the fluorescence intensity for the complex emission band (Figure 6), illustrating the ratiometric response of receptors **2a-b** to different Hg^{2+} concentrations. The number of necessary metal equivalents to achieve a plateau was at about 30 equivalents for compounds **2a-b**.

<Figure 6>

From the results of the spectrofluorimetric titrations in MeCN/H₂O (7:3) for compounds **2a-b**, it was possible to calculate association constants (K_{ass}), the detection (LOD) and quantification (LOQ) limits, which are between 8 and 11 ppm (Table 3). Recently, several receptors have been reported for the detection and quantification of Hg²⁺ in organic and aqueous media, with limits of detection and quantification in the ppm-ppb range [1b,i].

<Table 3>

As can be seen by the LOD and LOQ data presented in Tables 2 and 3, the values obtained by spectrophotometric and spectrofluorimetric titrations are in agreement, especially for compound **2b**.

2.3. ¹H NMR titrations

The sensory behaviour observed by the spectrophotometric/spectrofluorimetric titrations was also confirmed by performing ¹H NMR titrations but due to the limited solubility of compounds **2a-d** in deuterated acetonitrile, the titrations were carried out with Hg²⁺ in acetone-*d*₆ at room temperature (representative example for compound **2b** in figure 7).

<Figure 7>

The signal of the indolyl NH appearing at about 10 ppm was further shifted downfield ($\Delta\delta \sim 0.8$ ppm) upon addition of up to 6 equivalents of Hg²⁺, thus suggesting that the interaction with the metal cation is occurring at this site. The chemical shifts of the remaining protons were unaffected by the metal interaction.

3. Conclusions

The selective determination of Hg²⁺ in MeCN/H₂O (7:3) solution among various transition metal cations was possible with novel arylfuryl-*bis*(indolyl)methane derivatives bearing different electron donor and acceptor substituents. All the compounds **2a-d** exhibited a selective and significant colour change from colourless to purple, whereas a marked quenching of the fluorescence was additionally observed for

compounds **2a-b**, making these compounds suitable for dual chromo- and fluorimetric sensing of Hg^{2+} in aqueous mixtures. The binding stoichiometry between the receptors and Hg^{2+} was found to be 1:1, and the results obtained through UV-vis and ^1H NMR titrations were found to be in agreement, suggesting the formation of a complex between the metal and the ligand through interaction with the indolyl NH group.

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Captions

Scheme 1. Synthesis of arylfuryl-*bis*(indolyl)methanes **2**.

Figure 1. Solid samples and MeCN/H₂O (7:3) solutions (10⁻⁴ M) of compounds **2a-d**.

Figure 2. Color changes of compound **2b** (10⁻⁴ M in MeCN/H₂O (7:3)) in the presence of 100 equiv. of Ca²⁺, Cd²⁺, Co²⁺, Cr³⁺, Cu²⁺, Fe²⁺, Fe³⁺, Hg²⁺, Pd²⁺, Ni²⁺ and Zn²⁺ (in the form of tetrafluoroborate or perchlorate salts).

Figure 3. Relative fluorimetric response (I/I_0) of compound **2a** in the presence of 100 equiv of Ca²⁺, Cd²⁺, Co²⁺, Cr³⁺, Cu²⁺, Fe²⁺, Fe³⁺, Hg²⁺, Pd²⁺, Ni²⁺ and Zn²⁺, as a function of metal concentration in acetonitrile/H₂O (7:3, v/v) solution.

Figure 4. Spectrophotometric titrations of **2a** (A), **2b** (B), **2c** (C) and **2d** (D) with addition of increasing amounts of Hg²⁺ in MeCN/H₂O (7:3). The inset represents the normalized absorption at: 290 and 516 nm (A); 290 and 543 nm (B); 267 and 518 nm (C) and 377 and 505 nm (D) ($[\mathbf{2a-d}] = 2.5 \times 10^{-5}$ M, T = 298 K).

Figure 5. Job's plot for the complexation of compounds **2a-d** with Hg²⁺, indicating the formation of 1:1 complexes. The total $[\mathbf{2a-d}] + [\text{Hg}^{2+}] = 4.0 \times 10^{-5}$ M.

Figure 6. Spectrofluorimetric titrations of **2a** (A, B) and **2b** (C, D) with the addition of increasing amounts of Hg²⁺ in MeCN/H₂O (7:3) at pH 7.0 aqueous solution. The inset represents the normalized fluorescence intensity at 425 nm (A), 585 nm (B), 358 nm (C) and 625 nm (D) (T= 298 K; $[\mathbf{2a}] = [\mathbf{2b}] = 2.5 \times 10^{-5}$ M, $\lambda_{\text{exc(A)}} = 290$ nm, $\lambda_{\text{exc(B)}} = 516$ nm, $\lambda_{\text{exc(C)}} = 290$ nm, $\lambda_{\text{exc(D)}} = 543$ nm).

Figure 7. Partial ¹H NMR spectra of **2b** (1.4 x 10⁻² M) in acetone-*d*₆ in (a) the absence and (b) the presence of 1.0, (c) 2.0, (d) 4.0 and (e) 6.0 equiv of Hg²⁺.

Table 1. Yields, IR, UV-vis absorption and emission data for arylfuryl-*bis*-(indolyl)methanes **2a-d**, in MeCN/H₂O (7:3) solution.

^a For the NH proton (in acetone-*d*₆). ^b For the NH stretching band recorded in Nujol.

Table 2. Absorption and limit of detection (LOD) and limit of quantification (LOQ) data upon titration of arylfuryl-*bis*-(indolyl)methanes **2a-d** with Hg²⁺, in MeCN/H₂O (7:3) solution (L, ligand; L-Hg²⁺, complex ligand-metal).

Table 3. Fluorescence data and limit of detection (LOD) and limit of quantification (LOQ) data upon titration of arylfuryl-*bis*-(indolyl)methanes **2a-d** with Hg²⁺, in MeCN/H₂O (7:3) solution (L, ligand; L-Hg²⁺, complex ligand-metal).

Figures

Figure 1.

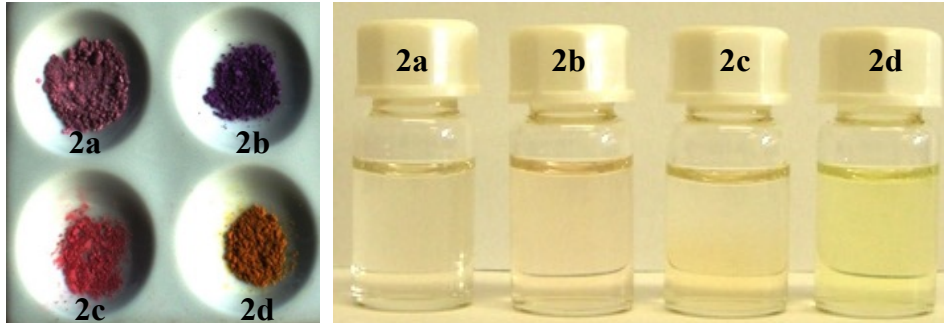


Figure 2.

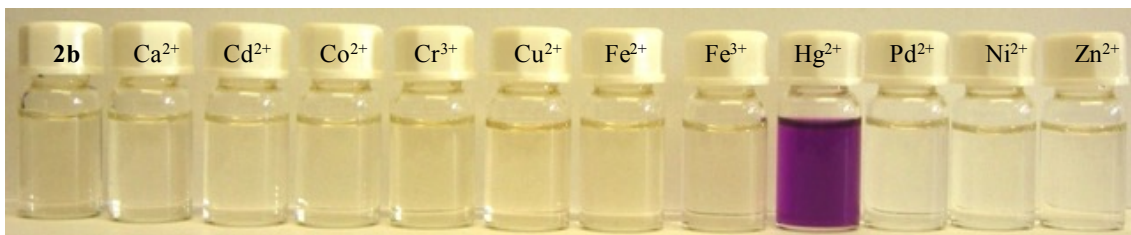


Figure 3.

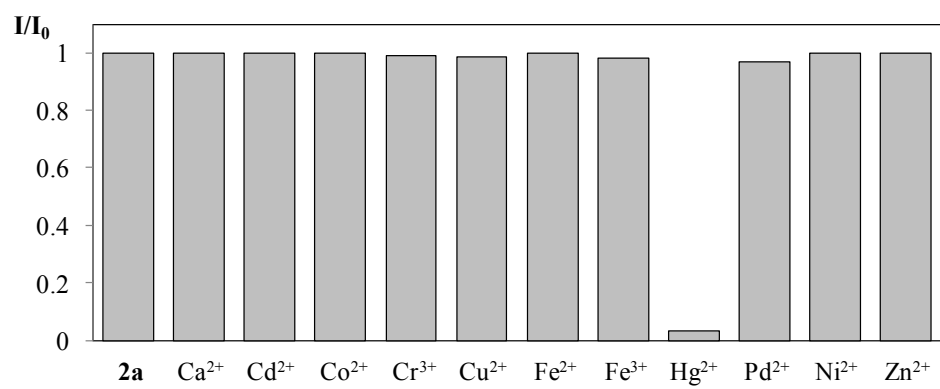


Figure 4.

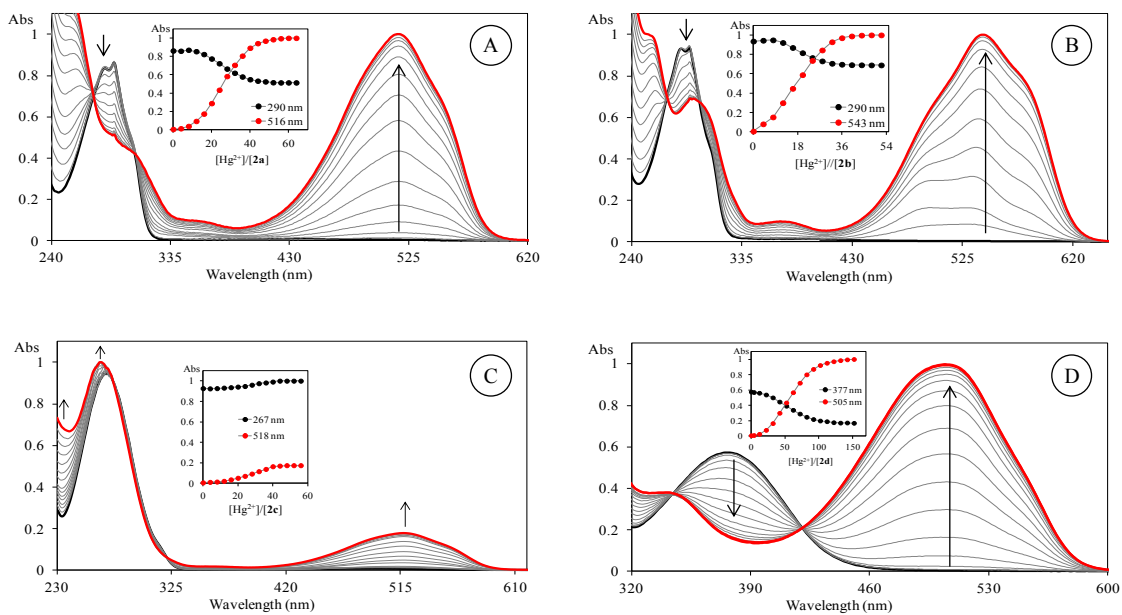


Figure 5.

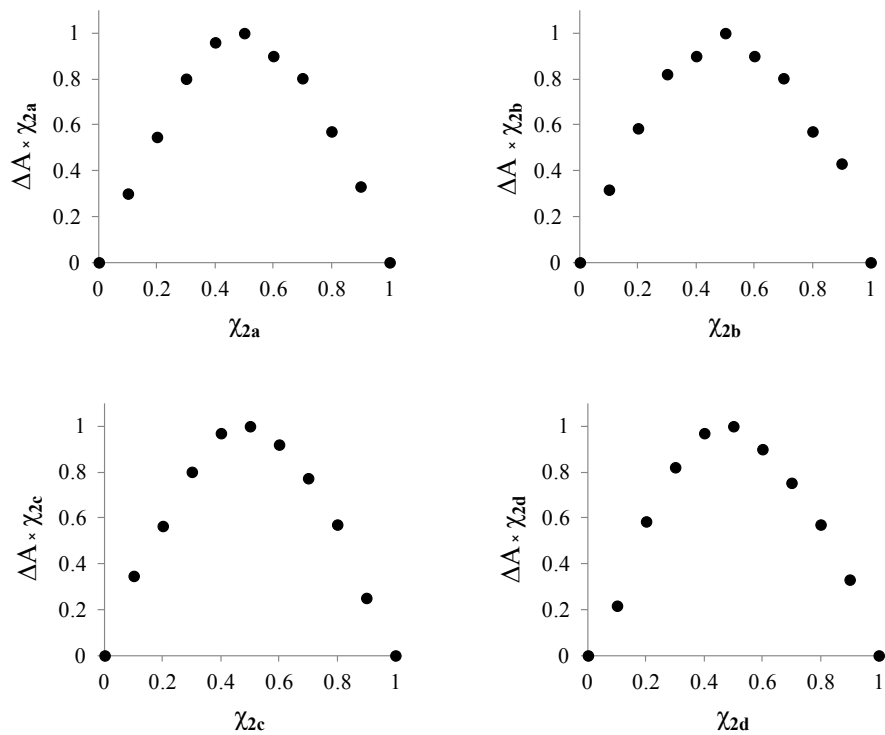


Figure 6.

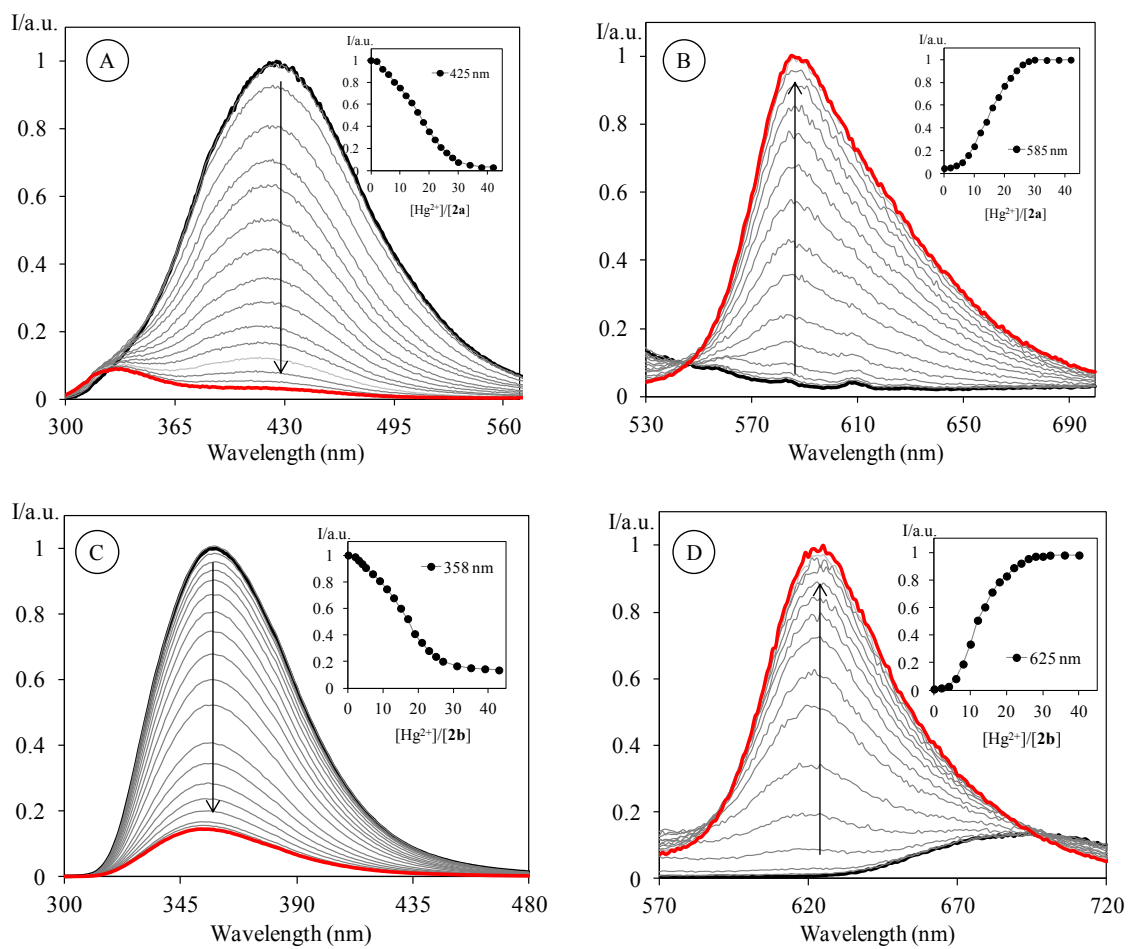
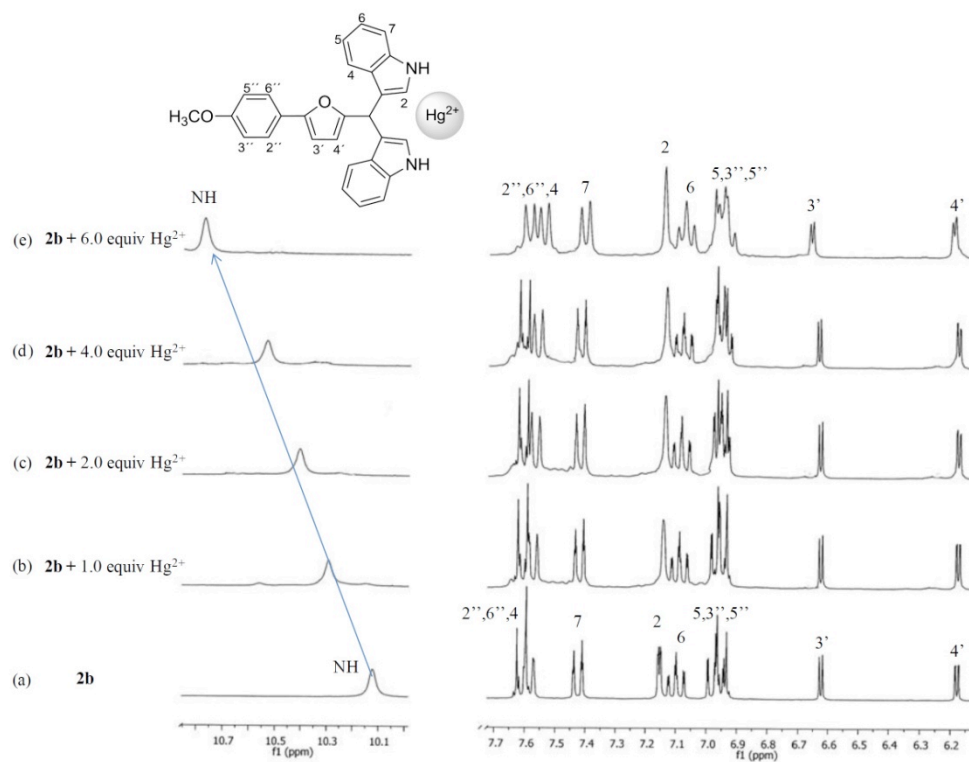


Figure 7.



Tables

Table 1

Cpd	R	Yield (%)	δ_{H} (ppm) ^a	IR ν (cm ⁻¹) ^b	UV-vis	Fluorescence		
					λ_{abs} (nm)	λ_{em} (nm)	Stokes' shift (cm ⁻¹)	Φ_{F}
2a	H	50	10.11	3412	288	425	10953	0.21
2b	OMe	40	10.10	3411	289	358	6549	0.58
2c	Br	54	10.10	3409	287	387	11613	0.01
2d	NO ₂	65	10.15	3409	370	412	2755	0.001

Table 2

Cpd.	UV-vis		Isosbestic points (nm)	Log K_{ass}	LOD (ppm)	LOQ (ppm)
	L λ_{abs} (nm)	L-Hg ²⁺ λ_{abs} (nm)				
2a	290	516	274, 307	2.01 ± 0.03	20.2	67.5
2b	290	543	271, 299	2.90 ± 0.01	10.6	35.6
2c	270	518	---	1.90 ± 0.03	24.7	82.2
2d	377	505	344, 420	1.76 ± 0.02	31.7	105.7

Table 3

Cpd	Fluorescence				Log K_{ass}	LOD (ppm)	LOQ (ppm)
	L λ_{emis} (nm)	Stokes shift (cm ⁻¹)	L-Hg ²⁺ λ_{emis} (nm)	Stokes shift (cm ⁻¹)			
2a	425	10953	585	2285	3.801 ± 0.003	8.5	28.3
2b	358	6549	625	2416	3.691 ± 0.005	10.8	36.1

Schemes

Scheme 1.

