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FULL PAPER

Rhenium(I) tricarbonyl complexes with mercaptoimidazolylborate ligands bearing piperazine fragments

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Received 8th July 2002, Accepted 9th September 2002
First published as an Advance Article on the web 16th October 2002

Reaction of an adequate borohydride salt with the functionalized mercaptoimidazoles $timH^{Me,pip}$ **1** or $timH^{Me,CH_2\text{-}pip}$ **2** have led to $Na[H_2B(tim^{Me,pip})_2]$ **3**, $Na[H_2B(tim^{Me,CH_2\text{-}pip})_2]$ **4**, $Li[H(Ph)B(tim^{Me})(tim^{Me,pip})_2]$ **6** and $Li[H(Ph)B(tim^{Me})(tim^{Me,CH_2\text{-}pip})_2]$ **7** ($timH^{Me}$ = 1-methyl-2-mercaptoimidazole; $timH^{Me,pip}$ = 1-methyl-5-[(4-(2′-methoxyphenyl)-1-piperazinyl)carbonyl]-2-mercaptoimidazole; $timH^{Me,CH_2pip}$ = 1-methyl-5-[(4-(2′-methoxyphenyl)-1-piperazinyl)methyl]-2-mercaptoimidazole). These symmetric and assymmetric functionalized bis(mercaptoimidazolyl)borates, carrying a piperazine fragment, react readily with $(NEt)_4[Re(CO)_3Br_3]$ giving $[Re\{\kappa^3\text{-}H(\mu\text{-}H)B(tim^{Me,pip})_2\}(CO)_3]$ **8**, $[Re\{\kappa^3\text{-}H(\mu\text{-}H)B(tim^{Me,CH_2\text{-}pip})_2\}(CO)_3]$ **9**, $[Re\{\kappa^3\text{-}Ph(\mu\text{-}H)B(tim^{Me})(tim^{Me,pip})\}(CO)_3]$ **10** and $[Re\{\kappa^3\text{-}Ph(\mu\text{-}H)B(tim^{Me})(tim^{Me,CH_2\text{-}pip})\}(CO)_3]$ **11**. The organometallic complexes **8**–**11** are valuable models for the development of specific radiopharmaceuticals for imaging serotonergic CNS receptors. The new compounds (**1**–**11**) have been characterized by the usual analytical techniques (C, H, N analysis; IR and ^1H NMR spectroscopies), and by X-ray diffraction analysis in the case of **8**.

Introduction

In recent years, it has been demonstrated that organometallic complexes with the *fac*-$[M(CO)_3]^+$ (M = ^{99m}Tc, $^{186/188}Re$) moieties can be applied in the labelling of biologically active molecules, such as peptides, central nervous system (CNS) ligands or sugar derivatives.[1] However, for applying these labelling tools adequate bifunctional chelator systems are needed. Our research group has been exploring the utility of poly(mercaptoimidazolyl)borates for labelling biomolecules with the organometallic moieties *fac*-$[M(CO)_3]^+$ (M = ^{99m}Tc, $^{186/188}Re$).[2] We have shown that these soft sulfur donor ligands are able to stabilize Re(I) or Tc(I) tricarbonyl complexes of the type $[M\{\kappa^3\text{-}R(\mu\text{-}H)B(tim^{Me})_2\}(CO)_3]$ (M = Re, ^{99m}Tc; R = H, Me, Ph), which display unprecedented and quite robust agostic B–H ··· M interactions. At non-carrier added level (^{99m}Tc), these complexes can be prepared with high radiochemical yield and with high specific activity, being remarkably stable under aqueous and aerobic conditions.[2] Moreover, preliminary biodistribution studies in mice have shown that these neutral and lipophilic ^{99m}Tc complexes are able to cross the blood–brain barrier.[3] These features highlighted the usefulness of bis(mercaptoimidazolyl)borates as bifunctional chelators for the labelling of CNS-receptor avid molecules. The coupling of the biologically active substrates to the chelator framework can be done using different strategies, one of them being through the mercaptoimidazolyl rings. Using this approach, one or two biomolecules can be coupled to the framework, in an asymmetric or symmetric fashion, as illustrated in Fig. 1.

This contribution reports our efforts on the derivatization of bis(mercaptoimidazolyl)borate anchors with CNS receptor avid molecules, while maintaining their ability to stabilize organometallic complexes with the *fac*-$[M(CO)_3]^+$ (M = Tc, Re) moieties. As a lead structure for the biologically active fragment, we have focused on 1-(2-methoxy)arylpiperazine derivatives, which are among the most thoroughly studied molecules for the targeting of the 5-HT_{1A} subclass of serotonergic receptors.[4] Herein, we describe the preparation of 1-methyl-5-[(4-(2′-methoxyphenyl)-1-piperazinyl)carbonyl]-2-mercaptoimidazole **1** and 1-methyl-5-[(4-(2′-methoxyphenyl)-1-piperazinyl)methyl]-2-mercaptoimidazole **2**, as well as the synthesis and characterization of the new symmetric and asymmetric borate ligands, $Na[H_2B(tim^{Me,pip})_2]$ **3**, $Na[H_2B(tim^{Me,CH_2\text{-}pip})_2]$ **4**, $Li[H(Ph)B(tim^{Me})(tim^{Me,pip})_2]$ **6** and $Li[H(Ph)B(tim^{Me})(tim^{Me,CH_2\text{-}pip})_2]$ **7**. Reactions of the starting material $(NEt_4)_2[ReBr_3(CO)_3]$ with these novel functionalized hydroborates have been investigated and the resulting Re(I) tricarbonyl complexes $[Re\{\kappa^3\text{-}H(\mu\text{-}H)B(tim^{Me,pip})_2\}(CO)_3]$ **8**, $[Re\{\kappa^3\text{-}H(\mu\text{-}H)B(tim^{Me,CH_2\text{-}pip})_2\}(CO)_3]$ **9**, $[Re\{\kappa^3\text{-}Ph(\mu\text{-}H)B(tim^{Me})(tim^{Me,pip})\}(CO)_3]$ **10** and $[Re\{\kappa^3\text{-}Ph(\mu\text{-}H)B(tim^{Me})(tim^{Me,CH_2\text{-}pip})\}(CO)_3]$ **11** will be also reported. All of the new compounds (**1**–**11**) have been fully characterized, including by X-ray diffraction analysis in the case of **8**.

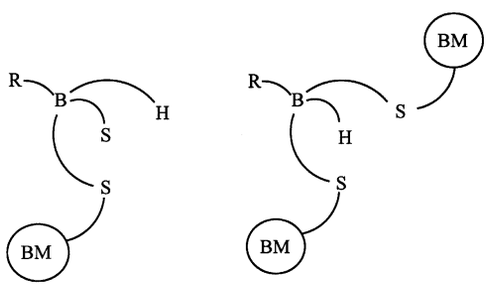

Fig. 1 Derivatization of bis(mercaptoimidazolyl)borates with biomolecules (BM) through the mercaptoimidazolyl rings.

Results and discussion

Synthesis and characterization of functionalized bis(mercaptoimidazolyl)borates

As referred to above, a straightforward way to achieve the derivatization of bis(mercaptoimidazolyl)borates is through

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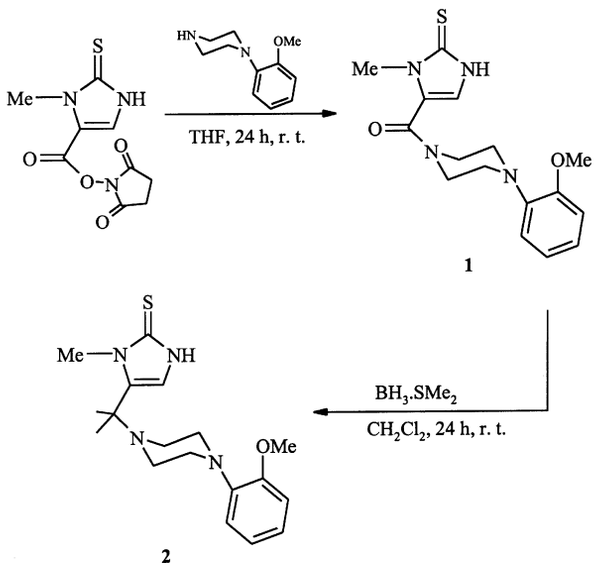
 DOI: 10.1039/b206603n



Scheme 1

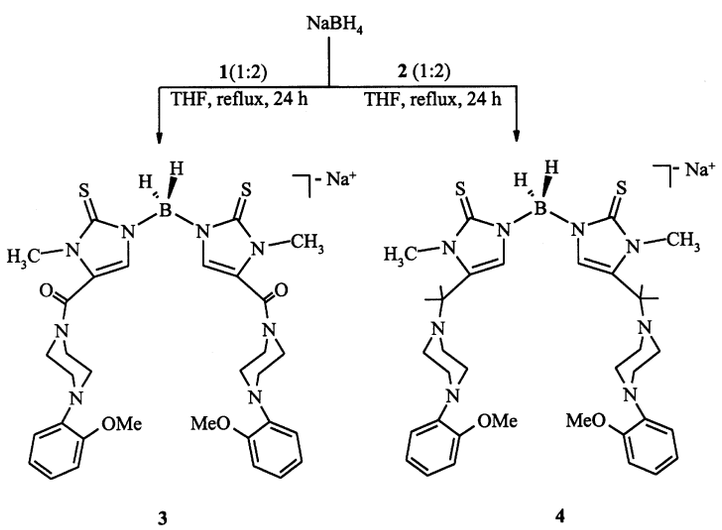
incorporation of the piperazine groups into the mercaptoimidazolyl rings. To accomplish this task, we have reacted the activated ester [(1-methyl-2-mercaptoimidazol-5-yl)-carbonyl]succinimide[5] with 1-(2-methoxyphenyl)piperazine, as indicated in Scheme 1. This reaction led to the synthesis of the novel 1-methyl-5-[(4-(2′-methoxyphenyl)-1-piperazinyl)-carbonyl]-2-mercaptoimidazole **1** ($tim^{Me,pip}$), in moderate yield (56%). Compound **1** was reduced to the respective tertiary amine by reaction with $BH_3{\cdot}SMe_2$ (Scheme 1).[6] The reduction ran efficiently, leading to the new derivative 1-methyl-5-[(4-(2′-methoxyphenyl)-1-piperazinyl)methyl]-2-mercaptoimidazole **2** ($tim^{Me,CH_2\text{-}pip}$), which was isolated in fair yield (55 %). The functionalized mercaptoimidazoles **1** and **2** were further used to prepare symmetric and asymmetric bis(mercaptoimidazolyl)-borates by reaction with suitable borohydrides.

The symmetric ligands $Na[H_2B(tim^{Me,pip})_2]$ **3** and $Na[H_2B(tim^{Me,CH_2\text{-}pip})_2]$ **4** were synthesized by reaction of sodium borohydride with **1** and **2**, respectively (Scheme 2). Both reactions were performed under reflux, in THF solution, and were followed by ^{11}B NMR spectroscopy. Ligands **3** and **4** were isolated, in a pure form, by successive recrystallizations from THF/n-hexane.

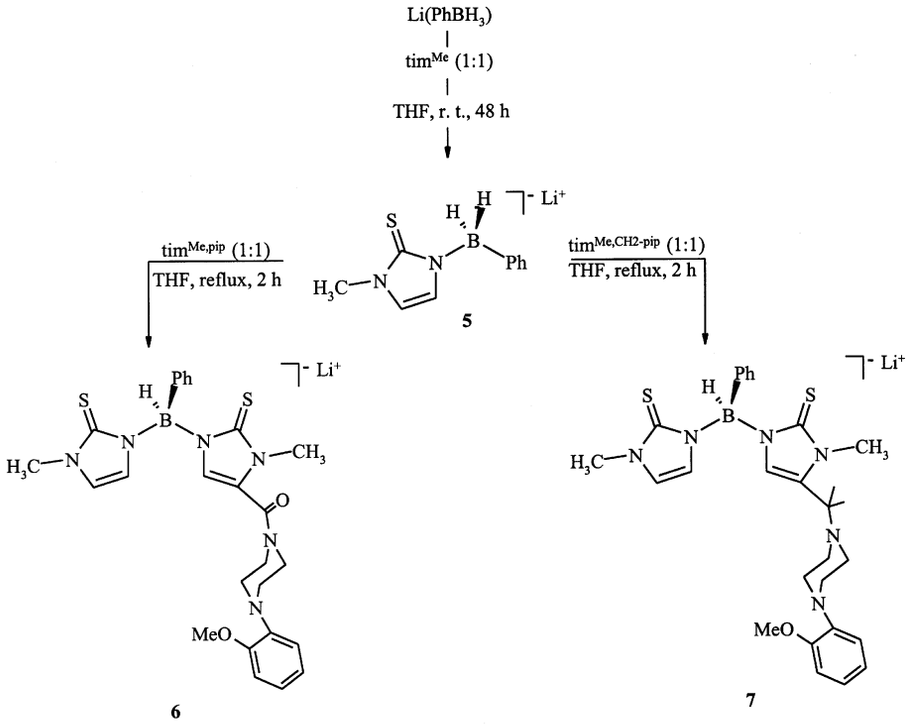
For the synthesis of asymmetric bis(mercaptoimidazolyl)-borates we devised a strategy which lies on the formation of an intermediary mono(mercaptoimidazolyl)borate, containing a 1-methyl-2-mercaptomercaptoimidazolyl ring, which is further reacted with a mercaptoimidazole bearing a piperazine moiety. As indicated in Scheme 3, the preparation of the mono(mercaptoimidazolyl)borate intermediate involved the reaction of $Li(PhBH_3)$ with 1-methyl-2-mercaptoimidazole in THF, at room temperature. The course of this reaction was followed by ^{11}B NMR spectroscopy. After 48 h, there was complete consumption of $Li(PhBH_3)$ and formation of a unique hydroborate derivative, which has been identified as $Li[H_2(Ph)B(tim^{Me})]$ **5** by ^1H and ^{11}B NMR spectroscopies. In CD_3CN, the ^{11}B NMR spectrum of **5** displays a triplet centred at 35.20 ppm, confirming the linkage of two hydrogen atoms to the boron atom. The ^1H NMR spectrum of **5** shows a set of resonances consistent with the presence of one phenyl group (Ph) and one 1-methyl-2-mercaptoimidazolyl ring (tim^{Me}): δ 7.15 (2H, d, J = 6.9 Hz, Ph); 6.99 (2H, tr, J = 6.0 Hz, Ph); 6.88 (1H, tr, J = 7.5 Hz, Ph), 6.67 (1H, d, J = 1.8 Hz, C*H*, tim^{Me}); 6.54 (1H, d, J = 1.8 Hz, C*H*, tim^{Me}); 3.46 (3H, s, CH_3, tim^{Me}).

For the synthesis of **6** and **7**, $Li[H_2(Ph)B(tim^{Me})]$ **5** was generated *in situ* and then reacted with the functionalized mercaptoimidazoles $tim^{Me,pip}$ **1** or $tim^{Me,CH_2\text{-}pip}$ **2** (Scheme 3). After refluxing for 2 h, the solvent was removed and the crude products analysed by ^1H NMR to confirm the presence of the ligands $Li[H(Ph)B(tim^{Me})(tim^{Me,pip})]$ **6** or $Li[H(Ph)B(tim^{Me})(tim^{Me,CH_2\text{-}pip})]$ **7**. Compounds **6** and **7** were obtained in low isolated yields as their purification required successive recrystallizations from THF/n-hexane, necessary to remove $Li[H(Ph)B(tim^{Me})_2]$. This compound appears when **5** is refluxed in THF, due to a redistribution process.

The functionalized mercaptoimidazoles (**1** and **2**) and the corresponding symmetric (**3** and **4**) or asymmetric (**6** and **7**) hydroborate ligands have been characterized by ^1H NMR and IR spectroscopies. The most significant feature of the IR spectra of the hydroborate ligands is the presence of weak and broad bands centred at frequency values spanning from 2350 to 2420 cm^{-1}, which were attributed to the B–H stretching vibrations.[2] In the case of **3** and **6**, their IR spectra display very intense bands centred at 1635 and 1610 cm^{-1} due to the C=O stretching vibration.[7] In the IR spectra of all compounds (**1**–**7**) the C=S stretching vibration appears as a medium intense band with frequencies between 740 and 760 cm^{-1}.[8] The ^1H NMR data obtained for compounds **1**–**7** are in accordance with the respective formulations (see Experimental section). In particular, the ^1H NMR spectra of **6** and **7** show resonances due to the protons of 2-mercaptoimidazole (tim^{Me}) and due to the functionalized mercaptoimidazoles ($tim^{Me,pip}$ or $tim^{Me,CH_2\text{-}pip}$), attesting to the asymmetric character of **6** and **7**.



Scheme 2



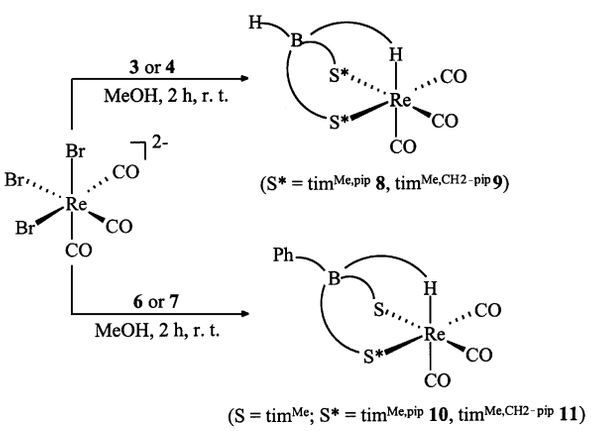
Scheme 3

The piperazinyl protons of **4** and **7**, resonating at frequencies between 2.50 and 2.96 ppm, are shielded in comparison with the corresponding protons in **3** and **6**, which appear between 2.95 and 3.75 ppm. This difference reflects the withdrawing electronic properties of the carbonyl group directly linked to the piperazine ring in **3** and **6**.

The functionalized mercaptoimidazolylborate ligands (**3**, **4**, **6** and **7**) are quite soluble in water, being remarkably stable towards aerial oxidation or hydrolysis, either in the solid state or in solution. Therefore, these functionalized hydroborates display the necessary requirements to be explored in radiopharmaceutical development.

Synthesis and characterization of Re(I) tricarbonyl complexes

As depicted in Scheme 4, $(NEt_4)_2[ReBr_3(CO)_3]$ reacts readily



Scheme 4

with ligands **3**, **4**, **6**, or **7**, affording the rhenium tricarbonyl complexes **8**–**11** in fair isolated yields (45–58%), after adequate work-up. The follow-up of these reactions by ^{1}H NMR in CD_3OD revealed that the starting material is converted into complexes **8**–**11** almost quantitatively, with only minor formation of impurities being detected. The moderate isolated yields can be justified by the loss of **8**–**11** during the respective purification procedures necessary to obtain strictly pure compounds.

Complexes **8**–**11** are yellow microcrystalline solids, stable towards aerial oxidation or hydrolysis, either in the solid state or in solution.

The IR spectra of **8**–**11** display weak bands in the range 2070 to 2170 cm^{-1}, assigned to ν(B–H $\cdots$ Re), which are strongly red-shifted compared to the B–H stretching frequencies in the free ligands or compared to the terminal ν(B–H) in the case of **8** and **9**.

The ^{1}H NMR data obtained for complexes **8**–**11** are in agreement with the proposed formulations. In particular, the ^{1}H NMR data indicate the presence of either functionalized or non-functionalized mercaptoimidazolyl rings and the presence of the piperazine moieties. In the case of **8** and **10**, the ^{1}H NMR pattern agrees with the symmetries found in the solid state. We should note that for complex **11**, in DMSO-d_6 the resonance due to the methylenic protons bridging the piperazinyl and mercaptoimidazolyl rings and one of the resonances due to the piperazinyl protons merge with the residual water signal. Unfortunately, compound **11** has a quite limited solubility in most common deuterated solvents, and we were unable to run the spectrum of **11** in other solvents. In agreement with the presence of quite strong agostic B–H $\cdots$ Re interactions, the ^{1}H NMR spectra of **8**–**11** show the presence of highfield shifted resonances due to the coordinated hydrogen atoms. These resonances appear at −6.58 and −6.74 ppm for the symmetric complexes (**8** and **9**), and at −5.41 and −5.42 ppm for the asymmetric ones (**10** and **11**).

The molecular structure of **8**, a symmetric complex, was confirmed by X-ray diffraction analysis. Selected bond lengths and angles are presented in Table 1, and in Fig. 2 is shown an ORTEP view of **8**. We were also able to obtain crystals of **10** suitable for X-ray diffraction analysis, but unfortunately of low quality. The best crystal measured did not provide a good quality data set for accurate bond distance and angle measurement, but the connectivity of the atoms in this asymmetric compound was determined unambiguously (Fig. 3). Compound **10** crystallizes from dichloromethane as pale yellow crystals in the monoclinic $P2_1/c$ space group, with cell

Table 1 Selected bond lengths (Å) and angles (°) for **8**

Re–C(1)	1.89(2)	Re–C(2)	1.90(2)
Re–S(1)	2.478(4)	Re–B	2.79(2)
C(1)–O(1)	1.15(2)	C(2)–O(2)	1.14(2)
C(11)–S(1)	1.704(11)		
C(1)–Re–C(2)	89.2(6)	C(2)–Re–C(2*)[a]	90.9(9)
C(1)–Re–S(1)	92.2(5)	C(2)–Re–S(1)	91.3(5)
C(2)–Re–S(1*)[a]	177.4(4)	S(1)–Re–S(1*)[a]	86.5(2)

[a] Equivalent atoms generated by the symmetry operation $x, -y + 0.5, z$.

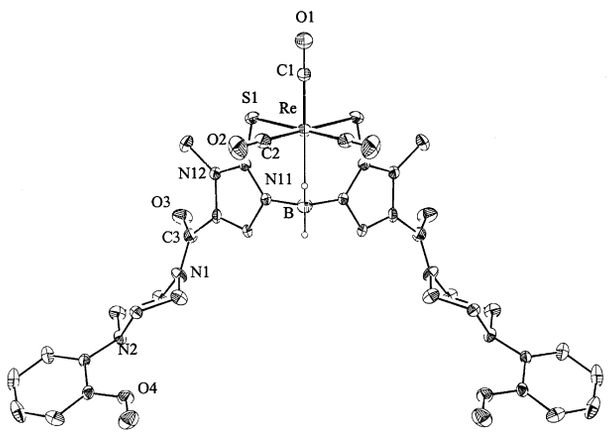


Fig. 2 ORTEP view of [Re{κ³-H(μ-H)B(tim^{Me,pip})$_2$}(CO)$_3$] **8**. Vibrational ellipsoids are drawn at the 20% probability level.

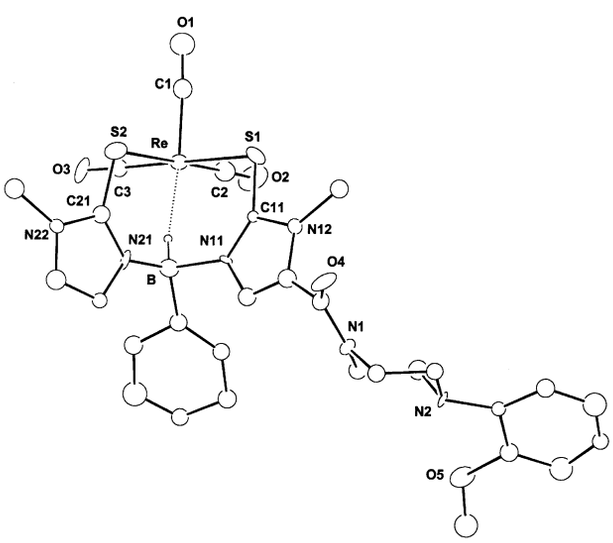


Fig. 3 ORTEP view of [Re{κ³-Ph(μ-H)B(tim^{Me})(tim^{Me,pip})}(CO)$_3$] **10**. Vibrational ellipsoids are drawn at the 20% probability level.

parameters $a = 10.393(2)$ Å, $b = 15.497(2)$ Å, $c = 19.900(3)$ Å, $\beta = 101.777(13)°$, $V = 3137.6(9)$ Å^3, $Z = 4$, $D_c = 1.695$ g cm^{-3}.

As can be seen in Fig. 2, **8** is a butterfly-shaped molecule that displays a crystallographic imposed mirror plane containing one of the CO ligands, the rhenium and boron atoms. The Re atom is in a slightly distorted octahedral coordination environment, one of the triangular faces being occupied by the three CO ligands. The remaining coordination positions are occupied by the thione sulfur atoms and by the hydrogen atom involved in the agostic B–H ··· Re interaction, the dihydrobis(mercaptoimidazolyl)borate acting as a tridentate (κ³-HS$_2$) donor ligand. The same coordination environment was found for complex **10** (Fig. 3). The X-ray structural analysis of **8** did not allow the direct localization of the hydrogen atom involved in the agostic interaction B–H ··· Re. The contributions of both B–H hydrogen atoms were included in calculated positions, constrained to ride on their boron atom. Nevertheless, the B ··· Re distance of 2.79(2) Å is clearly consistent with the presence of an agostic B–H ··· Re interaction in **8**, as would be expected from the spectroscopic properties of this complex. The B ··· Re distance, the average Re–C [1.90(1) Å] and Re–S [2.478(4) Å] distances in **8** are comparable to the values that we have previously reported for the correspondent distances in the non-functionalized complexes [Re{κ³-R(μ-H)-B(tim^{Me})$_2$}(CO)$_3$] (R = H, Me, Ph).[2] In respect to the functionalized dihydrobis(mercaptoimidazolyl)borate, the intraligand bond distances and angles are normal; both six-membered piperazinyl rings are in a chair conformation, avoiding in such a way any intramolecular repulsive interaction with the coordinated mercaptoimidazolyl rings.

Concluding remarks

Bis(mercaptoimidazolyl)borate ligands were successfully functionalized, in a symmetric or asymmetric fashion, with piperazine fragments which are part of a known antagonist (WAY 100 635) of the 5-HT$_{1A}$ subtype serotonergic receptors. The incorporation of the biologically active fragment did not disturb the coordination capabilities of the borate ligands towards the *fac*-[Re(CO)$_3$]$^+$ moiety,[2] and several novel Re(I) tricarbonyl complexes, **8**–**11**, with these functionalized ligands have been prepared. Complexes **8**–**11**, as indicated by spectroscopic data, contain a remarkably robust agostic B–H ··· Re interaction, which remains intact even in coordinating solvents such as water, methanol, tetrahydrofuran and dimethyl sulfoxide. These compounds can be seen as adequate surrogate molecules of ^{99m}Tc complexes potentially relevant in the development of specific radiopharmaceuticals for the targeting of 5-HT$_{1A}$ serotonergic receptors. ^{99m}Tc radiopharmaceuticals for *in vivo* imaging of 5-HT$_{1A}$ receptors have a well recognized clinical interest, as these biological structures are implied in a series of neurological diseases. However, so far, none of the evaluated ^{99m}Tc complexes have proved to be adequate for imaging the receptors *in vivo*.[4] Interestingly, the use of functionalized mercaptoimidazolylborates offers the opportunity of exploring the so-called bivalent approach, which relies on the use of two pharmacophores linked through a spacer in a single ligand.[9] This approach is one of the strategies currently being explored by medicinal chemists to design selective CNS receptor subtype ligands,[10] but remains unexplored in the field of radiopharmaceutical chemistry. Despite increasing the size of the ^{99m}Tc complexes, the bivalent approach is expected to be helpful in identifying more selective ^{99m}Tc radiopharmaceuticals for the targeting of CNS receptors.

Relative binding affinity (RBA) measurements of the symmetric or asymmetric rhenium complexes (**8**–**11**) are currently under way. These measurements are expected to assess whether the bivalent approach can enhance the binding affinity and selectivity to the 5-HT$_{1A}$ receptors. The introduction of different length spacers between the mercaptoimidazolyl and piperazinyl rings is also being explored, in order to evaluate the influence on the affinity and selectivity of the symmetric or asymmetric complexes.

Experimental

General procedures

The synthesis of the functionalized mercaptoimidazoles and of the corresponding hydroborate ligands were carried out under a nitrogen atmosphere using standard Schlenk techniques, while the synthesis of the rhenium complexes was performed under air. Tetrahydrofuran and CH_2Cl_2 were dried and distilled according to described procedures. All other solvents and

chemicals were used as purchased. The starting material $(NEt_4)_2[ReBr_3(CO)_3]$,[11] the organoborohydride $Li(PhBH_3)$[12] and [(1-methyl-2-mercaptoimidazol-5-yl)carbonyl]succinimide ($tim^{Me,NHS}$)[5] were prepared by the literature methods. ^{1}H NMR spectra were recorded on a Varian Unity 300 MHz spectrometer; ^{1}H chemical shifts were referenced with the residual solvent resonances relative to Me_4Si, and ^{11}B NMR chemical shifts were referenced externally with sodium borohydride. IR spectra were recorded as KBr pellets on a Perkin-Elmer 577 spectrometer. C, H and N analyses were performed on an EA110 CE Instruments automatic analyser. It was not possible to obtain accurate C, H, N analyses for **3**, **4**, **6** and **7**, although ^{1}H NMR analysis indicated that we had obtained pure compounds.

1-Methyl-5-[(4-(2′-methoxyphenyl)-1-piperazinyl)carbonyl]-2-mercaptoimidazole ($tim^{Me,pip}$) 1

To a suspension of the activated ester $tim^{Me,NHS}$ (1.940 g, 7.59 mmol) in THF was added, dropwise and at 0 °C, a solution of 2-methoxyphenylpiperazine (1.606 g, 8.35 mmol) (10% molar excess) in THF. The reaction mixture was allowed to warm to room temperature and was stirred for 24 h. After this time, compound **1** precipitated from the reaction mixtures and was recovered by filtration, followed by washing with 10% $NaHCO_3$ (20 ml) and water (20 ml). After drying under vacuum, compound **1** was obtained as a microcrystalline white solid (1.410 g, 56%). Found: C, 56.1; H, 6.6; N, 16.3. $C_{16}H_{20}N_4O_2S$ requires: C, 57.8; H, 6.0; N, 16.9%. ν_{max}/cm^{-1}: 1585vs (C=O), 760m (C=S). δ_H (CD_3CN): 6.91–6.94 (5H, m, C*H* + Ph), 3.77 (3H, s, O–CH_3), 3.73 (4H, m, N–CH_2), 3.53 (3H, s, N–CH_3), 3.02 (4H, m, N–CH_2).

1-Methyl-5-[(4-(2′-methoxyphenyl)-1-piperazinyl)methyl]-2-mercaptoimidazole ($tim^{Me,CH_2\text{-}pip}$) 2

To a suspension of **1** (1.196 g, 3.60 mmol) in CH_2Cl_2 was added dropwise 11 ml of 1.0 M $BH_3{\cdot}SMe_2$ in CH_2Cl_2, and the mixture was stirred for 24 h at room temperature. The reaction mixture was cooled in ice, and methanol was added dropwise until gas evolution ceased. After removal of the solvent under vacuum, 10 ml of methanol was added to the crude mixture and the resulting solution was refluxed for 1 hour. Methanol was evaporated and the crude product was purified by silica-gel flash chromatography using THF/n-hexane (50:50) as eluent. Removal of the solvent from the collected fractions gave a white residue, which was washed with n-hexane. The insoluble material was dried under vacuum to afford compound **2** as a microcrystalline white solid (0.629 g, 55%). Found: C, 59.0; H, 6.6; N, 16.2. $C_{16}H_{22}N_4OS$ requires: C, 60.4; H, 6.9; N, 17.6%. ν_{max}/cm^{-1} 740 m (C=S). δ_H (CD_3CN) 6.87–6.93 (4H, m, Ph), 6.63 (1H, s, C*H*), 3.79 (3H, s, O–CH_3), 3.54 (3H, s, N–CH_3), 3.39 (2H, s, CH_2), 2.98 (4H, br, N–CH_2), 2.54 (4H, br, N–CH_2).

$Na[H_2B(tim^{Me,pip})_2]$ 3

A suspension of $NaBH_4$ (0.100 g, 2.64 mmol) and $tim^{Me,pip}$ (1.753 g, 5.28 mmol) in THF was refluxed for 24 h. After cooling at room temperature the reaction mixture was filtered to remove any insoluble material, and the filtrate was concentrated under vacuum; upon addition of n-hexane compound **3** precipitated as a white microcrystalline solid (0.970 g, 53%). ν_{max}/cm^{-1}: 2410w (B–H), 1635s (C=O), 760m (C=S). δ_H (acetone-d_6): 7.40 (2H, s, C*H*), 6.87–6.96 (8H, m, Ph), 3.78 (6H, s, –OCH_3), 3.58 (8H, m, N–CH_2), 3.44 (6H, s, N–CH_3), 2.95 (8H, m, N–CH_2).

$Na[H_2B(tim^{Me,CH_2\text{-}pip})_2]$ 4

The preparation and recovery of **4** was carried out as described above for **1**. Starting from 0.026 g (0.69 mmol) of $NaBH_4$, compound **4** was obtained in the form of a white solid (236 mg, 51%). ν_{max}/cm^{-1}: 2350w (B–H), 750m (C=S). δ_H (CD_3CN): 6.86–6.91 (8 + 2H, m, C*H* and Ph), 3.78 (6H, s, O–CH_3), 3.48 (6H, s, N–CH_3), 3.34 (4H, s, N–CH_2), 2.96 (8H, br, N–CH_2), 2.51 (8H, br, N–CH_2).

$Li[H(Ph)B(tim^{Me})(tim^{Me,pip})_2]$ 6

To a solution of $Li(PhBH_3)$ (200 mg, 2.04 mmol) in THF was added dropwise a solution of 2-mercapto-1-methylimidazole (233 mg, 2.04 mmol) in THF, and the reaction mixture was stirred at room temperature for 48 h. After this time, solid $tim^{Me,pip}$ (679 mg, 2.04 mmol) was added to the reaction mixture and the resulting suspension was refluxed for 2 h. After cooling to room temperature, the reaction mixture was filtrated and the filtrate was concentrated to one third of its original volume. Upon addition of n-hexane, compound **6** precipitated as a microcrystalline white solid. Further purification of **6** was achieved by successive recrystallizations from THF/n-hexane (0.134 g, 12%). ν_{max}/cm^{-1}: 2400w (B–H), 1610s (C=O), 750m (C=S). δ_H (CD_3CN): 6.84–7.14 (1 + 9H, m, C*H* + Ph), 6.70 (1H, d, J_{H-H} = 2.1 Hz, C*H*), 6.57 (1H, d, J_{H-H} = 2.1 Hz, C*H*), 3.80 (3H, s, –OCH_3), 3.75 (4H, m, N–CH_2), 3.56 (3H, s, N–CH_3), 3.45 (3H, s, N–CH_3), 2.94 (4H, m, N–CH_2).

$Li[H(Ph)B(tim^{Me})(tim^{Me,CH_2\text{-}pip})_2]$ 7

Starting from 0.140 g (1.43 mmol) of $Li(PhBH_3)$, 0.164 g (1.44 mmol) of 2-mercapto-1-methylimidazole, and 0.455 g (1.43 mmol) of $tim^{Me,CH_2\text{-}pip}$, compound **7** was prepared and recovered as described above for **6** (0.075 g, 10%). ν_{max}/cm^{-1}: 2420w (B–H), 750m (C=S). δ_H (CD_3CN): 6.88–7.13 (9H, m, Ph), 6.69 (1H, d, J_{H-H} = 2.1 Hz, C*H*), 6.46 (1H, J_{H-H} = 2.1 Hz, C*H*), 6.38 (1H, s, C*H*), 3.79 (3H, s, –OCH_3), 3.54 (3H, s, N–CH_3), 3.47 (3H, s, N–CH_3), 3.34 (2H, s, CH_2), 2.97 (4H, m, N–CH_2), 2.50 (4H, m, N–CH_2).

General procedure for the synthesis of complexes 8–11

To a solution of $(NEt_4)_2[Re(CO)_3Br_3]$ (0.100 g, 0.13 mmol) in methanol was added a methanolic solution of the desired ligand, in a 1:1 molar ratio, and the mixtures were allowed to react for 2 h at room temperature. Complexes **8** and **11** precipitated from the respective reaction mixtures, and were recovered by filtration followed by washing with small portions of methanol. Complexes **9** and **10** were recovered by recrystallization from dichloromethane/n-hexane, after removal of methanol.

$[Re\{\kappa^3\text{-}H(\mu\text{-}H)B(tim^{Me,pip})_2\}(CO)_3]$ 8

Yield: 0.055 g, 45%. Found: C, 44.7; H, 4.4; N, 11.9. $C_{35}H_{40}BN_8O_7S_2Re$ requires: C, 44.4; H 4.2; N 11.9%. ν_{max}/cm^{-1}: 2450w (B–H), 2070w (Re ··· B–H), 1910vs and 2020vs (C≡O), 1630s (C=O), 770m (C=S). δ_H (DMSO-d_6): 7.70 (2H, s, C*H*), 6.82–6.96 (8H, m, Ph), 3.72 (6H, s, –OCH_3), 3.70 (8H, br, N–CH_2), 3.55 (6H, s, N–CH_3), 2.97 (8H, m, N–CH_2), −6.71 (1H, br, Re ··· *H*–B).

$[Re\{\kappa^3\text{-}H(\mu\text{-}H)B(tim^{Me,CH_2\text{-}pip})_2\}(CO)_3]$ 9

Yield: 0.055 g, 46%. Found: C, 46.2; H, 5.4; N, 11.7. $C_{35}H_{44}BN_8O_5S_2Re$ requires: C, 45.8; H, 4.8; N, 12.2%. ν_{max}/cm^{-1}: 2430w (B–H), 2150w and 2070w (Re ··· B–H), 2020vs and 1910vs (C≡O), 750m (C=S). δ_H(CD_3CN): 6.80–6.95 (2 + 8H, m, C*H* + Ph), 3.73 (6H, s, –OCH_3), 3.55 (6H, s, N–CH_3), 3.37 (4H, m, N–CH_2), 2.94 (8H, m, N–CH_2), 2.50 (8H, m, N–CH_2), −6.58 (1H, br, Re ··· *H*–B).

$[Re\{\kappa^3\text{-}Ph(\mu\text{-}H)B(tim^{Me})(tim^{Me,pip})\}(CO)_3]$ 10

Yield: 0.050 g, 48%. Found: C, 43.0; H, 3.1; N, 10.7. $C_{29}H_{30}BN_6O_5S_2Re$ requires: C, 43.3; H, 3.7; N, 10.5%. ν_{max}/cm^{-1}: 2170w (Re ··· B–H), 2020vs and 1910vs (C≡O). δ_H (CD_3CN): 7.32–7.38 (5H, m, Ph), 7.14 (1H, d, J_{H-H} = 2.1 Hz, C*H*), 6.80–6.96

Table 2 Crystallographic data for **8**

Chemical formula	$C_{35}H_{40}BN_8O_7S_2Re \cdot C_4H_8O \cdot H_2O$
Mol. wt.	1036.00
Crystal system	Orthorhombic
Space group	*Pnma*
a/Å	18.068(3)
b/Å	27.733(4)
c/Å	9.1500(1)
V/Å^3	4584.9(1)
Z	4
D_c/g cm^{-3}	1.501
μ/mm^{-1}	2.800
F(000)	2096
Index ranges	$-21 \le h \le 1$
	$-1 \le k \le 32$
	$-10 \le l \le 1$
θ Range/°	2.3–25.0
Reflections collected	4585
Independent reflections	4125 ($R_{int} = 0.0472$)
Data/restraints/parameters	3351/20/281
Goodness-of-fit on F^2	1.062
Final $R1$ [a] $[I > 2\sigma(I)]$/$wR2$ [b]	0.0700/0.1487
Large diff. peak/hole/e Å^{-3}	1.194/−0.945

[a] $R1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$. [b] $wR2 = [\Sigma(w(F_o^2 - F_c^2)^2)/\Sigma(w(F_o^2)^2)]^{0.5}$.

(1 + 4H, m, C*H* + Ph), 6.77 (1H, d, J_{H-H} = 2.1 Hz, C*H*), 3.81 (3H, s, O–CH_3), 3.69 (4H, m, N–CH_2), 3.62 (3H, m, N–CH_3), 3.58 (3H, s, N–CH_3), 2.97 (4H, m, N–CH_2), −5.41 (1H, br, Re ··· *H*–B).

[Re{κ^3-Ph(μ-H)B(tim^{Me})(tim$^{Me,CH_2\text{-}pip}$)}(CO)$_3$] 11

Yield: 0.060 g, 58%. Found: C, 43.5; H, 4.3; N, 10.6. $C_{29}H_{32}BN_6O_4S_2Re$ requires: C, 44.1; H, 4.1; N, 10.7%. ν_{max}/cm^{-1}: 2130w (Re ··· B–H), 2030vs and 1900vs (C≡O). δ_H (DMSO-d$_6$): 7.48 (1H, d, J_{H-H} = 2.1 Hz, C*H*), 7.38–7.32 (3H, m, Ph), 7.21 (2H, m, Ph), 6.98 (1H, d, J_{H-H} = 2.1 Hz, C*H*), 6.95 (1H, s, C*H*), 6.91–6.84 (4H, m, Ph), 3.74 (3H, s, O–CH_3), 3.59 (3H, s, N–CH_3), 3.56 (3H, s, N–CH_3), 2.92 (4H, br, N–CH_2), −5.42 (1H, br, Re ··· *H*–B).

X-Ray crystallographic analysis

A yellowish crystal of **8** was obtained by recrystallization from THF/n-hexane and fixed inside a thin-walled glass capillary. Data were collected at room temperature on an Enraf-Nonius CAD4-diffractometer with graphite-monochromatized Mo-Kα radiation, using a ω–2θ scan mode. Unit cell dimensions were obtained by least-squares refinement of the setting angles of 25 reflections with $16.5 < 2\theta < 29.6°$. A summary of the crystallographic data is given in Table 2. Data were corrected for Lorentz and polarization effects and for absorption by empirical corrections based on Ψ scans.[13] The heavy atom positions were located by Patterson methods using SHELXS-86.[14] The remaining atoms were located by successive difference Fourier maps and refined by least-squares refinements on F^2 using SHELXL-93.[15] A THF solvent molecule of crystallization was located in the Fourier difference map. A remaining residual peak was assigned as an oxygen atom of a water molecule. All the non-hydrogen atoms were refined with anisotropic thermal motion parameters and the contributions of the hydrogen atoms were included in calculated positions (except those of the water molecule). Atomic scattering factors and anomalous disperson terms were as in SHELXL-93.[15] The drawings were made with ORTEP-3,[16] and all the calculations were performed on a DEC α 3000 computer.

CCDC reference number 189597.

See http://www.rsc.org/suppdata/dt/b2/b206603n/ for crystallographic data in CIF or other electronic format.

Acknowledgements

This work has been partially supported by the FCT (POCTI/2001/QUI/42939) and by the Commission of the European Communities (COST action B12). R. G. and Y. H. X. thank the FCT for a PhD research grant and Post-doctoral Grant, respectively.

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