Structure-activity profiling of alkaloid natural product pharmacophores against a *Schistosoma* serotonin receptor

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**A R T I C L E   I N F O**

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**A B S T R A C T**

Serotonin (5-HT) is an important regulator of numerous aspects of flatworm biology, ranging from neuromuscular function to sexual maturation and egg laying. In the parasitic blood fluke *Schistosoma mansoni*, 5-HT targets several G-protein coupled receptors (GPCRs), one of which has been demonstrated to couple to cAMP and regulate parasite movement. This receptor, Sm.5HTR	extsubscript{a}, has been successfully co-expressed in mammalian cells alongside a luminescent cAMP-biosensor, enabling pharmacological profiling for candidate anti-schistosomal drugs. Here, we have utilized this assay to perform structure-activity investigations of 143 compounds containing previously identified alkaloid natural product pharmacophores (tryptamines, aporphines and protoberberines) shown to regulate Sm.5HTR	extsubscript{a}. These experiments mapped regions of the tryptamine pharmacophore amenable and intolerant to substitution, highlighting differences relative to orthologous mammalian 5-HT receptors. Potent Sm.5HTR	extsubscript{a} antagonists were identified, and the efficacy of these compounds were evaluated against live adult parasites cultured *ex vivo*. Such structure-activity profiling, characterizing the effect of various modifications to these core ring systems on Sm.5HTR	extsubscript{a} responses, provides greater understanding of pharmacophores selective for this target to aid future drug development efforts.

**1. Introduction**

Flatworm G-protein coupled receptors (GPCRs) are promising anthelminthic drug targets, given their role regulating movement, sexual maturation and egg laying (Patocka et al., 2014; Saberi et al., 2016; Chan et al., 2018; Hahnel et al., 2018). Over 200 million people worldwide are infected with the parasitic *Schistosoma* flatworms that cause the disease schistosomiasis (Hotez and Fenwick, 2009). This disease is largely treated by just one broad spectrum anti-schistosomal drug, praziquantel (PZQ) (Andrews et al., 1983). PZQ has been enormously beneficial in mitigating morbidity due to schistosomiasis and moving towards control of this disease, but drawbacks include PZQ’s ineffectiveness against immature parasites (Sabah et al., 1986), frequent side effects (Coulibaly et al., 2017), and cure rates that are rarely 100% effective (Olliaro et al., 2011; Coulibaly et al., 2017). Reliance on a single compound also raises the concern of emerging drug resistance. Therefore, there is a need for new anti-schistosomal drugs, either to supplement PZQ or to serve as an alternative in the event of treatment failure.

In the past several years, several studies have prioritized flatworm GPCRs as targets for drug development. RNAi and pharmacological approaches have identified serotonin (5-HT) GPCRs that control flatworm movement (Patocka et al., 2014; Chan et al., 2015), and GPCRs have also been implicated in flatworm sexual maturation and egg laying (Lu et al., 2016; Saberi et al., 2016; Wang et al., 2017; Chan et al., 2018). Additionally, while the parasite target(s) of PZQ remains undefined, our recent work has shown that the active R-PZQ enantiomer acts as a GPCR ligand, engaging human serotoninergic GPCRs that regulate mesenteric vessel tone (Chan et al., 2017). Precedent for engagement of GPCRs by PZQ should prioritize development of scalable functional assays to study flatworm GPCRs in more detail. One such approach centers upon co-expression of G	extsubscript{a}i/G	extsubscript{as} coupled GPCRs with GloSensor, a modified luciferase reporter which detects changes in cellular cAMP levels. This assay provides a high sensitivity and real-time readout of GPCR activity that can be scaled to miniaturized format. Previously, we optimized this methodology to enable pharmacological profiling of a schistosome serotoninergic GPCR (Sm.5HTR	extsubscript{a}) that controls worm movement (Patocka et al., 2014; Chan et al., 2016c).

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This approach implicated several classes of natural product heterocyclic alkaloid scaffolds as regulators of Sm.5HTRL activity (Chan et al., 2016b, 2016c, 2018). As natural products have a proven track record as leads for drug development (Newman and Cragg, 2012), we subsequently performed a more extensive analysis of structure-activity relationships for ergot alkaloids (Chan et al., 2018), and here in this study, tryptamine, aporphine and protoberberine scaffolds at this parasite GPCR. As these compounds are known regulators of mammalian 5-HT receptors (Cabella et al., 2009; Harding, 2016), the goal is to understand pharmacophore features that determine selectivity and potency for Sm.5HTRL to identify effective small molecule tools useful for probing schistosome biology as well as potential leads for anthelmintic development.

2. Materials and methods

Chemicals. A complete list of chemical structures and vendors for the compounds used in this work is provided in Supplemental Table 1. Compounds were selected from libraries sourced from the National Cancer Institute (NCI Natural Products Set IV) as well as commercial vendors (Tocris, Sigma Aldrich, Santa Cruz, Pharmeks and Abcam, see Supplemental Table 1 for catalog numbers) identified through searches of the ZINC and PubChem databases. Finally, several aporphine compounds were kindly provided by Wayne Harding (CUNY). The synthesis and activity profile of these compounds against mammalian bioamnergic receptors has been reported elsewhere (Chaudhary et al., 2009, 2011; Kapadia and Harding, 2015).

Cell culture. HEK-293 cells (ATCC CRL-1573, authenticated by STR profiling) were cultured in growth media consisting of DMEM supplemented with GlutaMAX (Gibco cat # 10566016), 10% heat inactivated fetal bovine serum and penicillin-streptomycin (100 units/mL, ThermoFisher). Individual compounds were also sourced from various vendors (Tocris, Sigma Aldrich, Santa Cruz, Pharmeks and Abcam, see Supplemental Table 1 for catalog numbers) identified through searches of the ZINC and PubChem databases. Finally, several aporphine compounds were kindly provided by Wayne Harding (CUNY). The synthesis and activity profile of these compounds against mammalian bioamnergic receptors has been reported elsewhere (Chaudhary et al., 2009, 2011; Kapadia and Harding, 2015).

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cAMP luminescence assays. Stable cell lines expressing the GloSensor-22F construct or both GloSensor-22F and Sm.5HTRL were cultured in T-75 flasks. The day prior to performing assays, cells were trypsinized (TrypLE Express, Gibco) and plated in solid white 96 well plates (Costar cat # 3917) at a density of 2.5x10^4 cells/well. One day later media was removed and replaced with assay buffer (HBSS buffered with HEPES (20 mM, pH 7.4) + BSA (0.1% w/v) and D-luciferin sodium salt (1 mg/mL, Gold Biotechnology). Plates were equilibrated at room temperature for 1 h, the phosphodiesterase inhibitor 3-Isobutyl-1-methylxanthine (IBMX 200 μM, Sigma Aldrich) was added, and plates were equilibrated for a further 30 min prior to test compound addition. Test compounds were added and luminescence was read for 45 min on a GloMax®-Multi Detection System plate reader (Promega) to identify agonist responses. Plates were removed, and a maximal concentration of serotonin (500 nM) was added to each well. Plates were immediately returned to the plate reader and read for a further 45 min to identify compounds with antagonist activity.

Adult schistosome mobility assays. Female Swiss Webster mice infected with S. mansoni cercariae (NMRI strain) were sacrificed 49 days post infection by CO2 euthanasia. Adult schistosomes were recovered by dissection of the mesenteric vasculature. Harvested schistosomes were washed in RPMI 1640 supplemented with HEPES (25 mM), 5% heat inactivated FBS (Gibco) and penicillin-streptomycin (100 units/mL). Worms were cultured overnight (37 °C/5% CO2) in vented 100 × 25 mm petri dishes (ThermoFisher cat # 4031) containing 50 mL of media. Movement assays were performed the next day. Male worms were transferred to a six well dish (4–5 individual worms per well) containing 3 mL media. For agonist assays, worms were incubated for 5 min in various concentrations of drug prior to acquiring videos of worm movement. For antagonist assays, worms were incubated for 1 h in test compound, and then a maximal concentration of serotonin (200 μM) was added before videos were acquired. Imaging was performed using a Zeiss Discovery v20 stereomicroscope and a QICAM 12-bit cooled color CCD camera controlled by Metamorph imaging software (version 7.8.1.0). Recordings (1 min) were acquired at 4 frames per second, saved as an image stack, and movement analyzed using ImageJ software as described in (Chan et al., 2016c). Data represents mean ± standard error for ≥ 3 independent experiments. Animal work was carried out with the oversight and approval of the Laboratory Animal Resources facility at the Medical College of Wisconsin. All animal experiments followed ethical regulations approved by the Medical College of Wisconsin IACUC committee.

3. Results

The schistosome serotonin (5-HT) receptor Sm.5HTRL was expressed in mammalian HEK-293 cells alongside the GloSensor 22-F cAMP luminescent reporter (Chan et al., 2016a, 2016c). Addition of 5-HT caused a rapid increase in cAMP-dependent luminescence in cells

![image](https://example.com/image.png)

Fig. 1. Functional expression of Sm.5HTRL. (A) Kinetics and (B) dose-response curves for 5-HT evoked luminescence in Sm.5HTRL expressing cells (solid symbols) and a negative control cell line lacking Sm.5HTRL (open symbols). (C) Pharmacophores assayed for activity against Sm.5HTRL. Ring systems are shown with numbering referred to throughout this manuscript. Clockwise from top: tryptamine, protoberberine, aporphine (benzylisoquinoline scaffold highlighted in bold).
expressing Sm.5HTR₅ (Fig. 1A). This increase was dose-dependent (EC₅₀ 94 ± 18 nM) and not observed in cells expressing the GloSensor 22-F reporter alone (Fig. 1B). The sensitivity and selectivity of this response was explored for three classes of heterocyclic scaffolds – tryptamine derivatives, aporphines and protoberberines. The core structures of these groups, and scaffold numbering nomenclature, are shown in Fig. 1C.

3.1. Modifications of the tryptaminergic pharmacophore impair agonist activity Sm.5HTR₅

First, various tryptamine derivatives were selected based on their activity at mammalian serotonergic GPCRs: the majority of which were substituted at the terminal amine and/or the C-5 position. For example, 5-carboxamidotryptamine (5-CT) and 5-methoxytryptamine (5-MeOT) bind to and are potent full agonists at the mammalian 5-HT₇ receptors (Bard et al., 1993; Shen et al., 1993) that are orthologous to Sm.5HTR₅ (Patocka et al., 2014; Chan et al., 2016c). N-methylserotonin, methylated at the terminal nitrogen, is also a full agonist at mammalian 5-HT₇ receptors (Powell et al., 2008).

In the Sm.5HTR₅ activity assay, the terminal amine of 5-HT accommodated the addition of methyl groups: both N-methylserotonin (N-MS) and bufotenine (5-OH-DMT) elevated cAMP with an Emax of 59 ± 2% relative to 5-HT (Fig. 2A). However, while the single methyl substitution on N-MS had little effect on potency (EC₅₀ 154 ± 11 nM, compared to 94 ± 18 nM for 5-HT), the dimethyl substitution on 5-OH-DMT decreased potency by an order of magnitude (EC₅₀ 2.4 ± 0.2 μM). α-methylserotonin (αM), methylated at the α position of the ethylamine side chain, was a low potency, partial agonist (Emax of 59 ± 2% relative to 5-HT; Fig. 2A).

In contrast, the 5-OH group present on serotonin was poorly tolerant to modification. Tryptamine (T', Fig. 2B), which is unsubstituted at the C-5 position, displayed negligible activity at Sm.5HTR₅. Substitutions at the C-5 position with amide or methoxy groups to produce 5-carboxamidotryptamine (5-CT) and 5-methoxytryptamine (5-MeOT) respectively, were poorly tolerated. Both compounds were inactive at Sm.5HTR₅ (Fig. 2B). Smaller C-5 substitutions, as seen in 5-methyllryptamine (5-MT) or 5-bromotryptamine (5-BrT), were better tolerated as these compounds displayed partial agonist activity (Fig. 2B). All compounds tested harboring dual substitutions at both the C-5 and terminal amine positions compared with 5-HT were inactive at Sm.5HTR₅. These analogs included the psychedelic tryptamine derivatives 5,N,N-dialyl-5-methoxytryptamine (5-MeO-DALT), 5-methoxy-N,N-dimethyltryptamine (5-MeO-DMT), N-methyltryptamine (N-MT) and N,N-dimethyltryptamine (DMT, Fig. 2C). None of the compounds identified as Sm.5HTR₅ agonists displayed activity against HEK-293 cells expressing the GloSensor-22F reporter alone (Supplemental Fig. 1).

3.2. Functional characteristics of the aporphine alkaloid scaffold at Sm.5HTR₅

The aporphine alkaloids are tetracyclic benzylisoquinolines that exhibit a range of activities at mammalian bioaminergic GPCRs (Cabedo et al., 2009; Harding, 2016). Numerous naturally occurring (Indra et al., 2002; Farrell et al., 2016) and synthetic (Linnanen et al., 2001; Chaudhary et al., 2009, 2011; Kapadia and Harding, 2015) aporphines are potent antagonists of mammalian serotonin receptors, and preliminary structure-activity profiling of this chemical series has been performed on Sm.5HTR₅ (Chan et al., 2016a). Based on these data, we expanded our study to encompass 89 aporphine structures.

Compounds containing the aporphine core ring structure were curated from the NCi and TimTec natural product libraries (Supplemental Table 1) and screened at an initial concentration of 10 μM. None of the tested aporphines showed agonist activity. Full concentration-inhibition curves were generated from hits that blocked 5-HT evoked cAMP generation, as well as related analogs with substitutions to provide insight into structure-activity relationships at Sm.5HTR₅. In total, concentration-response curves were generated for 83 aporphines, and this compound series demonstrated a gradation of inhibitory potencies at Sm.5HTR₅ (Fig. 3A). A subset of 9 ligands (Fig. 3A) were identified with an IC₅₀ ≤ 500 nM (inhibition of 500 nM 5-HT, a maximal concentration) and calculated affinity, pKi ≥ 7.0, estimated using the Cheng-Prusoff equation. Another 20 aporphines displayed pKi values between 6.9 and 6.0 (IC₅₀ < 5.5 μM, Fig. 3A).

Potent compounds clustered in several chemical series (Fig. 3A, inset). These analogs typically possessed methoxy modifications on aporphine rings A (C-1, C-2 or C-3 position) or D (C-9 and/or C-10 position) - either as “open” (as seen with nuciferine, compound 4b) or “closed” dioxolane ring groupings (as seen with nantenine. Compound 2a). Other substitutions were identified that were poorly tolerated. These included, (i) addition of bulky substituents to the aporphine nitrogen on ring B (Fig. 3B), (ii) unsaturation of the ring C, C-6a – C-7 bond: D-glaucine and L-nuciferine were antagonists with respective pKis of 6.8 and 7.1, but dehydroglaucine and dehydronuciferine were both inactive (Fig. 3C) and (iii) substitution of the C-3 position on ring A (Fig. 3D).

3.3. Functional characteristics of the protoberberine scaffold at Sm.5HTR₅

Protoberberines are another class of tetracyclic benzylisoquinolines that display antagonism at Sm.5HTR₅. Rotundine is a constituent of traditional Chinese herbal medicine preparations, with activity against both cestodes (Das et al., 2009; Gogoi and Yadav, 2017) and schistosomules and adult worms (Chan et al., 2016c). Therefore, we examined the e-activity of a mini-library of this chemical series against Sm.5HTR₅ (Fig. 3A), including a subset of 9 ligands (Fig. 3A) were identified that were poorly tolerated. These included, (i) addition of bulky substituents to the aporphine nitrogen on ring B (Fig. 3B), (ii) unsaturation of the ring C, C-6a – C-7 bond: D-glaucine and L-nuciferine were antagonists with respective pKis of 6.8 and 7.1, but dehydroglaucine and dehydronuciferine were both inactive (Fig. 3C) and (iii) substitution of the C-3 position on ring A (Fig. 3D).

3.4. Sm.5HTR₅ ligands alter the mobility of adult schistosomes cultured ex vivo

Sm.5HTR₅ is required for worm movement (Patocka et al., 2014) and Sm.5HTR₅ ligands can stimulate or block movement in larval schistosomes and adult worms (Chan et al., 2016a, 2016c). Therefore, we examined the effects of several substituted tryptamines (Sm.5HTR₅ agonists) and benzylisoquinolines (Sm.5HTR₅ antagonists) against adult schistosomes to assess whether these hits were active and whether they recapitulated structure-activity profiles observed against Sm.5HTR₅ in vitro. Tryptaminergic Sm.5HTR₅ agonists stimulated worm movement, although with decreased potency relative to results from in vitro cAMP

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Consistent with assays on Sm.5HTRL, substitution of the terminal amine was tolerated. N-methylserotonin (N-MS) was a full agonist increasing movement by 252 ± 9%, comparable to the 5-HT evoked-increase of 224 ± 17%. The indole C-5 position was amenable to slight modifications. 5-methyltryptamine (5-MT) stimulated movement, but only at high concentrations in the hundreds of micromolar. 5-methoxytryptamine (5-MeOT) stimulated movement, which contrasts with a lack of agonist activity at Sm.5HTRL (Figs. 5A and 2B). 5-carboxamidotryptamine (5-CT) did not stimulate movement, consistent with this compound being inactive at Sm.5HTRL. DMT, which is modified at both the indole C-5 and terminal amine, also had no effect on worm movement, mirroring the observed lack of activity at Sm.5HTRL.

Next, the aporphine and protoberberine Sm.5HTRL antagonists were tested on live worms to assess whether these compounds inhibited 5-HT evoked movement. Worms were incubated in compound for 1 h, after which a maximal dose of serotonin (200 μM) was added to stimulate motility. Several aporphines resembling nuciferine were studied. Nuciferine was the most potent antagonist of worm movement, inhibiting 5-HT evoked movement at concentrations as low as 100 nM (Fig. 5B). Compound phar025462, a nuciferine derivative with a charged nitrogen and a closed dioxolane ring in place of methoxy groups, and compound 785177, which substitutes the nuciferine A-1 methoxy with an hydroxy group, both inhibited 5-HT evoked movement, albeit with lower potency in the 1–10 μM range (Fig. 5B). The compound MDO-NPA, which potently inhibited Sm.5HTRL (pKi = 7.0), was relatively inactive on adult worms with inhibition of 5-HT not
surpassing 50% even at 10 μM (Fig. 5B).

Of the protoberberines, the Sm.5HTRL antagonist L-rotundine, the inactive analog D-rotundine and the closely related palmatine were screened on live worms. As expected, L-rotundine inhibited 5-HT evoked movement at concentrations ≥ 1 μM, while D-rotundine and palmatine showed no inhibition of 5-HT evoked movement at concentrations as high as 50 μM (Fig. 5C).

4. Discussion

These data highlight the structure-activity profile of tryptamine- and benzylisoquinoline-based analogs on a schistosome 5-HT receptor (Sm.5HTR$_r$) that controls worm movement. 5-HT has long been recognized as an important regulator of schistosome neuromusculature (Hillman et al., 1974; Tomosky et al., 1974; Patocka et al., 2014), and 5-HT receptors have been advanced as appealing targets for anthelminthic drug development (Mansour, 1979, 1984; Geary et al., 1992). The successful functional expression and miniaturization of a Sm.5HTR$_r$ profiling assay has enabled high-throughput compound screens to identify ligands with potential anti-schistosomal activity (Chan et al., 2018). Given these data validating Sm.5HTR$_r$ as a viable anti-schistosomal drug target, and the precedent of both tryptaminergic and benzylisoquinoline natural products as serotonergic ligands (Cabedo et al., 2009; Nichols, 2012; Harding, 2016) and antiparasitic compounds (Bonne, 1919; Iwasa et al., 1999; Nkwengoua et al., 2009; Das et al., 2009; Shahinas et al., 2012; Gogoi and Yadav, 2017), we performed a more detailed exploration of the properties of these pharmacophores that determine their efficacy as Sm.5HTR$_r$ ligands and activity against ex vivo cultured parasites.

4.1. Tryptaminergic ligand SAR at Sm.5HTR$_r$

Substituted tryptamines with modifications to the C-5 and terminal amine often display agonist activity against mammalian serotonergic receptors (Plasat et al., 1993; Shen et al., 1993; Shulgin, 1997; Powell et al., 2008; Nichols, 2012). Compounds with subtle modifications to the terminal amine retained agonist activity at Sm.5HTR$_r$ (Fig. 2A), but the pharmacophore was poorly tolerant to substitution at the C-5 position (Fig. 2B). The poor activity of 5-CT and 5-MeOT at Sm.5HTR$_r$ contrasts with the action of these ligands as full agonists at the orthologous human 5-HT7 receptor (Plasat et al., 1993). Given that the amino acid sequence of Sm.5HTR$_r$ shares just 40% similarity with the human ortholog, it is not surprising that the two GPCRs exhibit unique pharmacological sensitivities. A possible reason for the inactivity of the

Fig. 3. Structure-activity relationship of aporphine alkaloids at Sm.5HTR$_r$. (A) Affinity of 84 aporphines screened against Sm.5HTR$_r$, with pKi estimated using the Cheng-Prusoff equation. Inset - tree resulting from hierarchical clustering of structures, with most potent hits (pKi > 7.0) denoted with black symbols, and hits with pKi between 6.0 and 6.9 denoted with gray circles. Bottom – structures of the nine most potent compounds. (B) Structure activity profile of a nantenine-like aporphine series with modifications to the basic B-6 nitrogen. (C) Effect of dehydrogenation of the C-6a/C-7 bond of either D-glaucine or L-nuciferine. (D) Effect of various modifications to the D-glaucine A4 position resulting in a loss of activity at Sm.5HTR$_r$.
C-5 substituted tryptamines at Sm.5HTR<sub>7</sub> is that mutation of the glutamic acid at the 7.35 position of the human 5-HT<sub>7</sub> receptor abrogates 5-CT binding and function (Impellizzeri et al., 2015). This site varies in the schistosome receptors (phenylalanine), as well as the invertebrate <i>C. elegans</i> SER-7 receptor (aspartic acid) which is also refractory to 5-CT (Hobson et al., 2006). This difference, as well as the finding that neither DMT or related derivatives were active on Sm.5HTR<sub>7</sub> (Fig. 2C), despite their activity on mammalian serotonergic receptors (Shen et al., 1993; Keiser et al., 2009; Ray, 2010; Cozzi and Daley, 2016), advances our pharmacological understanding of the unique pharmacological signatures of host and parasite receptors. Other examples include the ergot alkaloid ergotamine, a potent antagonist at the human 5-HT<sub>7</sub> receptor (Wacker et al., 2013) but full agonist at Sm.5HTR<sub>7</sub> (Chan et al., 2018), as well as the commonly used 5-HT<sub>7</sub> chemical probe SB-269970, which is inactive at Sm.5HTR<sub>7</sub> (Chan et al., 2016c). These data emphasize the need for considerable caution when using pharmacological probes developed against mammalian targets to study invertebrate GPCRs, while revealing opportunities for developing parasite-selective ligands.

4.2. Determinants of benzylisoquinoline antagonism of schistosome serotonin receptors

Our previous work identified the benzylisoquinolines rotundine (Chan et al., 2016c) and nuciferine (Chan et al., 2016a) as potent antagonists at Sm.5HTR<sub>7</sub> and inhibitors of schistosome movement prompting exploration of compounds containing these ring systems in further detail. A thorough analysis of 117 benzylisoquinoline structures identified only antagonist hits. The strictly antagonist profile associated with this scaffold (Figs. 3 and 4) contrasts with the agonist/partial agonist profile of the tested tryptamine derivatives (Fig. 2) and the mixed agonist/antagonist profile of ergot alkaloids reported elsewhere (Chan et al., 2018).

Of the aporphine compounds tested, the most potent antagonists had a 1,2,9,10- substituted pattern, with methoxy groups or a dioxolane ring attached to the A and D rings of the aporphine core (nantenine, boldine, D-glaucine). The stereochemistry of the B6-B6a bond did not seem crucial – the levo structure L-nuciferine and dextro structures D-glaucine, boldine and nantenine were all potent antagonists (Fig. 3). However, saturation of the C ring at this position was important; dehydrogenation of the C-6a–C-7 bond of either D-glaucine or L-nuciferine resulted in a loss of activity (Fig. 3C). In addition to nuciferine, boldine and D-glaucine, which were previously identified as Sm.5HTR<sub>7</sub> antagonists (Chan et al., 2016c), we have shown that nantenine and ocoteine-like aporphines are also potent Sm5HTRL antagonists (pKi > 7.0, Fig. 3).

The protoberberine skeleton is similar to the aporphine skeleton – both share a benzylisoquinoline core. Consequently, it is unsurprising that like the aporphines, all active protoberberine compounds were...
antagonists. However, unlike the aporphines, the chirality of the stereocenter adjacent to the nitrogen atom seems crucial. For the antagonist D/L-rotundine, the L-rotundine enantiomer was active and D-rotundine displayed no activity at Sm.5HTR₅ (Fig. 4). This stereochémistry mirrors rotundine’s antagonism of mammalian bioaminergic GPCRs, where L-rotundine is the active enantiomer antagonizing mammalian dopamine D₁ (Mantsch et al., 2007) and serotonin 5HT₁A receptors (Mi et al., 2017). Like the active aporphines, L-rotundine possesses methoxy groups on the A and D rings. However, in the case of the protoberberines, formation of dioxolane rings - closing the methoxy positions on the A ring to produce canadine, or both the A and D rings to produce tetrahydrocopsitine - resulted in inactive compounds. The structure of xylopinine is identical to rotundine except for the movement of one methoxy from the D9 to the D11 position, but xylopinine was ~10 times less potent that rotundine, indicating that the stereochémistry of the methoxy groups are critical. This again differs from the aporphines, which accommodated various methoxy group placement around the A and D rings.

4.3. Correlation of Sm.5HTR₅ pharmacology with worm movement ex vivo

Schistosome movement is regulated by serotonergic signaling through Sm.5HTR₅ (Patocka et al., 2014), and there is a correlation between drug activity at this receptor and movement of parasites cultured ex vivo, with Sm.5HTR₅ agonists stimulating movement and Sm.5HTR₅ antagonists inhibiting movement (Chan et al., 2016a, 2016c, 2018). Tryptamnergic ligands were agonists at Sm.5HTR₅, and substitutions that eliminated activity at Sm.5HTR₅ also eliminated the ability of the same compounds to stimulate worm movement (5-CT and DMT, Fig. 2B&C and Fig. 5A). Similarly, substitutions that were tolerated in Sm.5HTR₅ cAMP assays were also generally tolerated in movement assays. For example, N-MS (differing from 5-HT by addition of a methyl group to the terminal amine) mirrored 5-HT in both assays. Modification of the tryptamine C-5 position resulted in compounds that were displayed impaired activity relative to 5-HT. Several compounds stimulated movement of worms ex vivo, but were inactive against Sm.5HTR₅. For example, 5-MeOT did not potently activate Sm.5HTR₅ (Fig. 2B), but potently stimulated movement in adult worms (Fig. 5A). While these differences may reflect differences between Sm.5HTR₅ function in live worms versus a mammalian expression system, an alternative interpretation is that 5-MeOT stimulates movement through other serotonin/bioaminergic GPCRs (Zamanian et al., 2011). This explanation can be tested as other schistosome GPCRs become amenable to functional profiling.

Reciprocally some compounds that are active against Sm.5HTR₅ show poor efficacy in ex vivo worm movement assays, perhaps due to pharmacokinetic variables such as whether the ligand is free to diffuse through the parasite tegument, is a substrate for active transporters such as SERT (Patocka and Ribeiro, 2007), or is degraded by worm enzymes such as monoamine oxidase (Nimmo-Smith and Raison, 1968). These variables may account for the right shifted dose response curves of serotonin in cell based cAMP assays (Fig. 1A) relative to movement assays (Fig. 5A). Similarly, benzylisoquinoline Sm.5HTR₅ antagonists were less potent on worms (Fig. 5B&C) than in cell-based cAMP assays (Figs. 3 and 4).

Human and parasite bioaminergic GPCRs are proven druggable targets (Evans and Gee, 1980; Hauser et al., 2017), and exploration of bioaminergic targets is a promising route for novel anti-schistosomal drug development (Wang et al., 2017; Camicia et al., 2018; Chan et al., 2018; Hahnel et al., 2018). One barrier to this work has been the functional expression of schistosome GPCRs in scalable assays that permit their thorough pharmacological characterization. While part of this difficulty may stem from the divergence of schistosome GPCRs relative to established model organisms (Sm.5HTR₅ has a 25% and 24% amino acid identity to human 5-HTR7 and C. elegans SER-7, respectively), this lack of conservation may also offer the opportunity to achieving a degree of pharmacological selectivity. This is supported by the structure-activity profiles outlined here, which highlight specific modifications that confer affinity as well as selectivity between worm and human orthologs. Expanding this approach to other schistosome GPCRs and other bioactive pharmacophores will be informative for future anthelmintic pharmacophore development and drug discovery initiatives.

Conflicts of interest

None.
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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jpddr.2018.09.001.

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