2,4-Diaminothieno[3,2-*d*]pyrimidines, a new class of anthelmintic with activity against adult and egg stages of whipworm

Short title: Diaminothienopyrimidines, a new chemotype for the control of whipworm

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Abstract

The human whipworm *Trichuris trichiura* is a parasite that infects around 500 million people globally, with consequences including damage to physical growth and educational performance. Current drugs such as mebendazole have a notable lack of efficacy against whipworm, compared to other soil-transmitted helminths. Mass drug administration programs are therefore unlikely to achieve eradication and new treatments for trichuriasis are desperately needed. All current drug control strategies focus on post-infection eradication, targeting the parasite *in vivo*. Here we propose developing novel anthelmintics which target the egg stage of the parasite in the soil as an adjunct environmental strategy. As evidence in support of such an approach we describe the actions of a new class of anthelmintic compounds, the 2,4-diaminothieno[3,2-*d*]pyrimidines (DATPs). This compound class has found broad utility in medicinal chemistry, but has not previously been described as having anthelmintic activity. Importantly, these compounds show efficacy against not only the adult parasite, but also both the embryonated and unembryonated egg stages and thereby may enable a break in the parasite lifecycle.

Author Summary

The human whipworm, *Trichuris trichiura*, infects around 500 million people globally, impacting on their physical growth and educational performance. There are currently huge mass drug administration (MDA) programs aiming to control whipworm, along with the other major soil transmitted helminths, *Ascaris* and hookworm. However single doses of albendazole and mebendazole, which are used in MDA, have particularly poor effectiveness against whipworm, with cure rates less than 40%. This means that MDA may not be able to control and eliminate whipworm infection, and risks the spread of resistance to albendazole and mebendazole in the parasite population.

We are attempting to develop new treatments for parasitic worm infection, particularly focused on whipworm. Herein we report the identification of a class of compounds, diaminothienopyrimidines (DATPs), which have not previously been described as anthelmintics. These compounds are effective against adult stages of whipworm, and also block the development of the model nematode *C. elegans.*

Our DATP compounds reduce the ability of treated eggs to successfully establish infection in a mouse model of human whipworm. These results support a potential environmental spray to control whipworm by targeting the infectious egg stage in environmental hotspots.

Introduction

Current anthelmintics

The benzimidazole anthelmintics albendazole and mebendazole are typically used to treat human whipworm infection but are compromised by lack of single-dose efficacy and the risk of resistance. Thus, existing drugs lack sufficient efficacy in mass drug administration (MDA) programs to adequately control or potentially eradicate whipworm. This is a major stumbling block in the WHO target to eliminate morbidity from soil transmitted helminthiases in children by 2020. The current approach for controlling soil-transmitted helminths such as *Trichuris* is mass drug administration of a single-dose of albendazole or mebendazole, typically repeated annually [1]. However for infection with *T. trichiura*, single doses of benzimidazoles lead to low cure rates, only 28% and 36% for albendazole and mebendazole respectively [2]. These cure rates are much lower than those of other major human soil-transmitted helminths, *Ascaris lumbricoides* and hookworm, demonstrating the need for improvements to therapy specifically targeting *Trichuris*. Indeed modelling studies have demonstrated that, due to these low cure rates, MDA with benzimidazoles does not interrupt whipworm transmission and thus cannot achieve eradication in many settings [3].

Furthermore, the experience from studies on veterinary parasites is that widespread usage of anthelmintics can lead to rapid development of resistance. The discovery of isolates of two species of gastrointestinal nematodes resistant to monepantel only four years after its introduction [4] underlies the real threat imposed by emerging drug resistance to control programmes. Indeed, the combination of MDA programs and low single-dose cure rates may facilitate the development of drug resistance in populations of human parasites. For example, resistance to benzimidazole drugs is caused by point mutations in β-tubulin. Such resistance mutations have been found in *T. trichiura* after mass drug administration [5], and have been found to increase in frequency after MDA. High frequency of resistance mutations in a population may be associated with lower egg-reduction rates after MDA [6]. Whilst there is no clear evidence yet of widespread anthelmintic resistance in human populations,

identification of new drugs with novel mechanisms of actions is warranted to slow the development of drug resistance.

Trichuris lifecycle

A *T. trichiura* infection becomes patent when adult female worms, embedded in the gut of the host, start to lay eggs. A single female worm can lay up to 20,000 eggs per day and these unembryonated eggs pass out with the faeces and embryonate in the soil. Development only proceeds further if the embryonated eggs are accidentally consumed via contact of the next host with contaminated food, water or soil. Once ingested, signals for hatching are received when the eggs reach the large intestine [7,8], the newly emerged first stage larvae invade the mucosal epithelium and development to the adult stage of the parasite occurs through a succession of larval moults. Importantly, even when active infections are successfully treated, hosts are constantly re-infected due to high levels of infective eggs present within the water and soil, which can remain viable for years.

Current anthelmintic programmes, including those targeting *Trichuris*, focus on post-infection eradication of existing infections. However, lifecycle stages outside of the host are also potential viable targets for small molecule drugs. Thus, both preventing egg embryonation and reducing the infectivity of embryonated eggs prior to ingestion offer targets that would break the parasite lifecycle.

Screening *ex vivo T. muris* adults for new anthelmintic chemotypes

The mouse whipworm, *T. muris*, is a convenient model of the human whipworm as it can be grown routinely in the laboratory via infection of severe combined immune deficiency (SCID) mice. Screening *ex vivo* adult *T. muris* has been used to test the anthelmintic activity of a variety of compounds, including approved drugs with the potential for repurposing, and also plant extracts [9–11]. We recently reported a small molecule screen utilising an automated assay for assessment of the motility of *ex vivo T. muris* adults. This screen led to the identification of a class of molecules termed dihydrobenzoxazepinone (DHB) which demonstrated encouraging activity in this assay, as well as the ability to reduce *in vivo* infectivity of treated eggs [12]. Most of the active molecules identified from

that screen belonged to the dihydrobenz[*e*][1,4]oxazepin-2(3*H*)-one chemotype, but interestingly one additional active was from a completely different structural class. Here we report the identification, synthesis and characterisation of this second chemotype, which has not previously been described as having anthelmintic activity, the 2,4-diamino thieno[3,2-*d*]pyrimidines (henceforth called diaminothienopyrimidines or DATPs).

Materials and methods

Ethics statement

All animal experiments were approved by the University of Manchester Animal Welfare and Ethical Review Board and performed under the regulation of the Home Office Scientific Procedures Act (1986) and the Home Office project licence 70/8127.

In vivo culture of *Trichuris muris*

T. muris worms were cultured using severe combined immune deficiency (SCID) mice, at the Biological Services Facility at the University of Manchester. Male and female mice were infected with 200 infective embryonated *T. muris* eggs via oral gavage. Thirty-five days later, the mice were sacrificed. Adult *T. muris* were obtained from the intestine as previously described [12]. Worms were maintained in Roswell Park Memorial Institute (RPMI) 1640 media supplemented with penicillin (500 U/mL) and streptomycin (500 µg/mL) at approximately 37 °C and studied on the same day.

Ex vivo T. muris adult maintenance for motility screen

Individual adult worms were added to wells containing 75 µL of RPMI-1640 medium, penicillin (500 U/mL), streptomycin (500 µg/mL) plus 1% v/v final concentration of dimethylsulfoxide (DMSO) or compound dissolved in DMSO. Plates were incubated at 37 °C, 5% CO_2. Motility was determined after 24 hours.

Automated motility assay

An automated system was used to quantify worm movement. An earlier version of this system has been previously described [13,14]. Two hundred frame movies of the whole plate were recorded at 10 frames per second and then motility determined by an algorithm based on thresholding pixel variance over time [15]. Dose-response curves were calculated with the four factor log-logistic model using the R package *drc* [16] or using GraphPad Prism.

Chemical synthesis

Thin layer chromatography (TLC) was performed on aluminium sheets coated with 60 F_{254} silica. All solvents are used anhydrous unless stated otherwise. NMR spectra were recorded on Bruker AV400 (400 MHz), Bruker AVII 500 (500 MHz) or AVIIIHD 600 (600 MHz) instruments in the deuterated solvent stated. All chemical shifts (δ) are quoted in ppm and coupling constants (*J*), which are not averaged, in Hz. Residual signals from the solvents were used as an internal reference using the stated deuterated solvent. Infrared spectra were recorded on a Perkin-Elmer 1750 IR Fourier Transform spectrophotometer using thin films on a diamond ATR surface (thin film). Only the characteristic peaks are quoted. Melting points were determined using a Stanford Research Systems EZ-Melt. Low resolution mass spectra (*m/z*) were recorded on an Agilent 6120 spectrometer and high resolution mass spectra (HRMS *m/z*) on a Bruker microTOF mass analyzer using electrospray ionization (ESI).Compounds were synthesised from commercially available starting materials, and fully characterised by Infrared (IR) Spectroscopy, Mass Spectrometry (ESI-MS, HRMS-ESI) and Nuclear Magnetic Resonance (^{1}H and ^{13}C NMR).

***2-Chloro-N-(2-(chlorophenoxy)ethyl)thieno[3,2-d]pyrimidin-4-amine* 2a**

To a 20 mL microwave vial containing 2,4-dichlorothieno[3,2-*d*]pyrimidine (1.50 g, 7.32 mmol, 1.0 equiv,) in 1,4-dioxane (15 mL) at RT was added 2-(2-chlorophenoxy)ethylamine (1.26 g, 7.32 mmol, 1.0 equiv.) and *N*,*N*-diisopropylethylamine (2.5 mL, 14.64 mmol, 2.0 equiv.) under an argon atmosphere. The vessel was sealed and the reaction heated at 80 °C for 3 h. The mixture was cooled to RT, concentrated *in vacuo* and the crude residue was purified by flash column chromatography (silica gel) to afford the title compound as an off-white solid (1.59 g, 64%).

mp = 118–119 °C; R_f = 0.2; ν_{max} (film)/cm^{-1} = 3398m (NH), 3088w (CH), 2970w (CH), 1586s (arom.), 1539m (arom.), 1483m (arom.); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.75 (1H, d, *J* = 5.4 Hz), 7.39 (1H, dd, *J* = 8.0, 1.6 Hz), 7.36 (1H, d, *J* = 5.4 Hz), 7.23 (1H, ddd, *J* = 8.3, 7.5, 1.6 Hz), 7.02 (1H, dd, *J* = 8.4, 1.4 Hz), 6.96 (1H, apparent td, *J* = 7.9, 1.3 Hz), 5.79 (1H, t, *J* = 5.4 Hz), 4.30 (2H, t, *J* = 5.0 Hz) 4.13 (2H, apparent q, *J* = 5.4 Hz); ^{13}C NMR (500 MHz, $CDCl_3$) δ 161.4, 158.1, 157.6, 153.9, 132.6,

130.5, 128.1, 124.9, 123.5, 122.6, 114.7, 114.3, 68.1, 40.5; LRMS (ESI^-) calculated for $[C_{14}H_{11}ON_3{}^{35}Cl_2{}^{32}S\text{-}H]^-$ = 338.0, found 337.9, $[M\text{-}H]^-$, 100%, calculated for $[C_{14}H_{11}ON_3{}^{35}Cl^{37}Cl\ {}^{32}S\text{-}H]^-$ = 340.0, found, 339.9 $[M\text{-}H]^-$, 60%; HRMS (ESI^+) calculated for $[C_{14}H_{11}ON_3{}^{35}Cl_2{}^{32}S+H]^+$ = 340.0073, found 340.0071, $[M+H]^+$.

2-Chloro-N-(2-phenoxyethyl)thieno[3,2-d]pyrimidin-4-amine **(2b)**

To a 20 mL microwave vial containing 2,4-dichlorothieno[3,2-*d*]pyrimidine (1.0 g, 5.0 mmol, 1.0 equiv.) in 1,4-dioxane (10 mL) at RT was added 2-phenoxyethylamine (0.6 mL, 5.0 mmol, 1.0 eq.) and *N*,*N*-diisopropylethylamine (1.7 mL, 10.0 mmol, 2.0 equiv.) under an argon atmosphere. The vessel was sealed and the reaction heated at 80 °C for 3 h. The mixture was cooled to RT, concentrated *in vacuo* and the crude residue was purified by flash column chromatography (silica gel) to afford the title compound as an off-white solid (1.23 g, 80%).

mp = 115.5–116.9 °C; R_f = 0.5 (EtOAc: Petroleum; 1:4); ν_{max} (film)/cm^{-1} = 3228w (NH), 3041w (CH), 2962w (CH), 1597s (arom.), 1581s (arom.), 1533m (arom.), 1511m (arom.), (arom.), 1496m (arom.), 1469m (arom.), 1434m (arom.); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.72 (1H, d, *J* = 5.4 Hz), 7.34 (1H, d, *J* = 5.4 Hz), 7.32-7.28 (2H, m), 6.97 (1H, app t, *J* = 7.3 Hz), 6.96 -6.92 (2H, m), 5.78 (1H, t, *J* = 4.8 Hz), 4.22 (2H, t, *J* = 5.1 Hz), 4.11-4.06 (2H, m); ^{13}C NMR (126 MHz, $CDCl_3$) δ 161.4, 158.4, 158.1, 157.5, 132.6, 129.7, 124.8, 121.5, 114.6, 114.1, 66.2, 40.9; LRMS (ESI^+) calculated for $[C_{14}H_{12}ON_3{}^{35}Cl_2{}^{32}S+H]^+$ = 306.0, found 306.0, $[M+H]^+$, 100%, calculated for $[C_{14}H_{12}ON_3{}^{35}Cl^{37}Cl^{32}S+H]^+$ = 308.0, found 308.0, $[M+H]^+$, 40%, calculated for $[C_{14}H_{12}ON_3{}^{35}Cl_2{}^{32}S+Na]^+$ = 328.0, found 328.0, $[M+H]^+$, 60%, calculated for $[C_{14}H_{12}ON_3{}^{35}Cl^{37}Cl^{32}S+Na]^+$ = 330.0, found 330.0, $[M+H]^+$, 20%; HRMS (ESI^+) calculated for $[C_{14}H_{12}ON_3{}^{35}Cl_2{}^{32}S+H]^+$ = 306.0462, found 306.0462, $[M+H]^+$.

General Synthetic Procedure

To a 10 mL microwave vial containing 2-chlorothieno[3,2-*d*]pyrimidine (1.0 equiv) in ^{i}PrOH (10 µL/mg chloride) at room temperature was added the requisite amine (10.0 equiv.) under an argon

183 atmosphere. The vessel was sealed and the mixture heated at 100°C for 16-24 h. The reaction was
184 cooled to ambient temperature (RT), concentrated *in vacuo* and the crude residue was purified by
185 flash column chromatography (silica gel).
186
187 ***N2-Methyl-N4-(2-phenoxyethyl)thieno[3,2-d]pyrimidine-2,4-diamine*** **(3a, OX02925)**
188 Following general procedure 1, the title compound was obtained from **2b** (600 mg, 1.96 mmol, 1.0
189 equiv.) and methylamine (2.0 M in THF, 9.8 mL, 19.6 mmol, 10.0 eq). Purification by flash column
190 chromatography ($MeOH:CH_2Cl_2$; 1:49 v/v) followed by trituration with cold Et_2O afforded the desired
191 product as a pale yellow viscous oil (526 mg, 89%).
192
193 R_f = 0.2 ($MeOH:CH_2Cl_2$; 1:49 v/v); ν_{max} (film)/cm^{-1} = 3418w (NH), 3232w (NH), 3038w (CH), 2936w
194 (CH), 1585s (arom.), 1532s (arom.), 1508s (arom.), 1460s (arom.), 1405m (arom.); ^{1}H NMR (500
195 MHz, $CDCl_3$) δ 7.55 (1H, d, *J* = 5.4 Hz), 7.33-7.28 (2H, m), 7.15 (1H, d, *J* = 5.4 Hz), 7.00-6.96 (1H,
196 m), 6.96-6.93 (2H, m), 5.16 (1H, brs), 4.83 (1H, brs), 4.21 (2H, t, *J* = 5.26 Hz), 4.02 (2H, m), 3.04
197 (3H, d, *J* = 5.04 Hz); ^{13}C NMR (126 MHz, $CDCl_3$) δ 161.9, 161.8, 158.5, 157.4, 130.4, 129.6, 124.1,
198 121.2, 114.5, 106.5, 66.6, 40.2, 28.7; LRMS (ESI^+) calculated for $[C_{15}H_{16}ON_4{}^{32}S+H]^+$ = 301.1, found
199 301.1 $[M+H]^+$, 100%; HRMS (ESI^+) calculated for $[C_{15}H_{16}ON_4C^{32}S+H]^+$ = 301.1119, found 301.1118
200 $[M+H]^+$.
201
202 ***N*4-(2-(2-Chlorophenoxy)ethyl)-N2-(2-methoxyethyl)thieno[3,2-d]pyrimidine-2,4-diamine (3b,**
203 **OX02926)**
204 Following general procedure 1, the title compound was obtained from **2a** (600 mg, 1.76 mmol, 1.0
205 equiv.) and 2-methoxyethylamine (1.5 mL, 17.6 mmol, 10.0 eq). Purification by flash column
206 chromatography ($MeOH:CH_2Cl_2$; 1:49 v/v) followed by trituration with cold Et_2O afforded the desired
207 product as an off-white solid (380 mg, 57%).
208
209 mp = 69–97 °C (Et_2O); R_f = 0.1 ($MeOH:CH_2Cl_2$; 1:49 v/v); ν_{max} (film)/cm^{-1} = 3424w (NH),
210 3304w (NH), 3076w (CH), 2949w (CH), 1606m (arom.), 1532s (arom.), 1476m (arom.), 1460m

(arom.), 1444m (arom.), 1412m (arom.); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (1H, d, *J* = 5.3 Hz), 7.39 (1H, dd, *J* = 7.9, 1.4 Hz), 7.23-7.21 (1H, m), 7.13 (1H, d, *J* = 5.3 Hz), 7.00-6.92 (2H, m), 5.29 (1H, s), 5.17 (1H, s) 4.27 (2H, t, *J* = 5.2 Hz), 4.05 (2H, apparent q, *J* = 5.4 Hz), 3.68-3.59 (4H, m), 3.40 (3H, s); ^{13}C NMR (151 MHz, $CDCl_3$) δ 161.8, 161.1, 157.3, 154.0, 130.5, 130.3, 127.8, 124.0, 123.3, 122.1, 114.3, 106.8, 71.6, 68.2, 58.7, 41.4, 39.9; LRMS (ESI^+) calculated for $[C_{17}H_{19}O_2N_4{}^{35}Cl^{32}S+H]^+$ = 379.1, found 379.1, $[M+H]^+$, 100%, calculated for $[C_{17}H_{19}O_2N_4{}^{35}Cl^{32}S+Na]^+$ = 401.1, found 401.1, $[M+Na]^+$, 10%; HRMS (ESI^+) calculated for $[C_{17}H_{19}O_2N_4{}^{35}Cl^{32}S+H]^+$ = $[M+H]^+$, 379.0990, found 379.0991 $[M+H]^+$.

***N4-(2-(2-chlorophenoxy)ethyl)-N2-(2-methoxybenzyl)thieno[3,2-d]pyrimidine-2,4-diamine* (3c, OX03143)**

Following general procedure 1, the title compound was obtained from **2a** (240 mg, 0.70 mmol, 1.0 eq.) and 2-methoxybenzylamine (0.92 mL, 7.0 mmol, 10.0 eq.). Purification by flash column chromatography (MeOH:CH_2Cl_2; 3:37 v/v) afforded the desired product (189 mg, 61%) as a thick pale yellow oil.

R_f = 0.4 (MeOH:CH_2Cl_2; 3:22 v/v); ν_{max} (film)/cm^{-1}= 3424w (NH), 3247w (NH), 2935w (CH), 1587m (arom.), 1553 (arom.), 1487 (arom.), 1461 (arom.); ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.54 (1H, d, *J* = 5.3 Hz), 7.38 (1H, dd, *J* = 8.1, 1.7 Hz), 7.36 (1H, s) 7.22 (1H, ddd, *J* = 9.5, 7.5, 1.6 Hz), 7.20 (1H, ddd, *J* = 8.2, 7.5, 1.6 Hz), 7.12 (1H, d, *J* = 5.3 Hz), 6.93 (1H, dt, *J* = 7.5, 1.5 Hz), 6.91 (1H, ddd, *J* = 8.1, 7.1, 1.1 Hz), 6.89 (2H, d, *J* = 7.9 Hz), 5.34 (1H, br), 5.29 (1H, t, *J* = 5.3 Hz), 4.68 (2H, d, *J* = 6.2 Hz) 4.20 (2H, t, *J* = 5.3 Hz), 4.04 (2H, apparent q, *J* = 5.3 Hz), 3.87 (3H, s); ^{13}C NMR (151 MHz, $CDCl_3$) δ 161.9, 161.2, 157.6, 157.4, 154.1, 130.5, 130.3, 129.1, 128.1 (x2), 127.8, 123.9, 123.3, 122.1, 120.3, 114.3, 110.1, 106.6, 68.2, 55.3, 41.4, 40.0; LRMS (ESI^+) calculated for $[C_{22}H_{21}O_2N_4{}^{35}Cl^{32}S+H]^+$ = 441.1, found 441.2, $[M+H]^+$, 100%; HRMS (ESI^+) calculated for $[C_{22}H_{21}O_2N_4{}^{35}Cl^{32}S+H]^+$ = 441.1147, found 441.1142 $[M+H]^+$.

***N4-(2-(2-chlorophenoxy)ethyl)-N2-methylthieno[3,2-d]pyrimidine-2,4-diamine* (3d, OX03147)**

Following general procedure 1, the title compound was obtained from **2a** (237 mg, 0.70 mmol) and methylamine (2.0 M in THF) (3.5 mL, 7.0 mmol, 10 eq). Purification by flash column chromatography (MeOH:CH_2Cl_2; 1:19 v/v) afforded the desired product (218 mg, 93%) as a pale brown oil.

R_f = 0.4 (MeOH:CH_2Cl_2; 1:19 v/v); ν_{max} (film)/cm^{-1}= 3247w (NH), 2940w (CH), 1588m (arom.), 1552m (arom.), 1510m (arom.), 1484m (arom.), 1461m (arom.), 1446m (arom.), 1406 (arom.); ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.56 (1H, d, *J* = 5.3 Hz), 7.38 (1H, dd, *J* = 7.9, 1.7 Hz) 7.21 (1H, ddd, *J* = 8.2, 7.5, 1.7 Hz), 7.15 (1H, d, *J* = 5.3 Hz), 6.98 (1H, dd, *J* = 8.2, 1.5 Hz), 6.95 (1H, dd, *J* = 7.5, 1.5 Hz) 5.31 (1H, t, *J* = 5.5 Hz), 4.84 (1H, s) 4.27 (2H, t, *J* = 5.4 Hz), 4.06 (2H, apparent q, *J* = 5.5 Hz), 3.04 (3H, d, *J* = 5.0 Hz); ^{13}C NMR (151 MHz, $CDCl_3$) δ 162.0, 161.9, 157.5, 154.2, 130.7, 130.5, 128.0, 124.2, 123.6, 122.3, 114.6, 106.9, 68.5, 40.1, 28.9; LRMS (ESI^+) calculated for $[C_{15}H_{15}ON_4{}^{35}Cl^{32}S+H]^+$ = 335.1, found 335.0, [M+H]+, 100%, calculated for $[C_{15}H_{15}ON_4{}^{37}Cl^{32}S+H]^+$ = 337.1, found 337.0, [M+H]+, 30%, HRMS (ESI^+) calculated for $[C_{15}H_{15}ON_4{}^{35}Cl^{32}S+H]^+$ = 335.0728, found 335.0725 $[M+H]^+$, calculated for $[C_{15}H_{15}ON_4{}^{37}Cl^{32}S+H]^+$ = 337.0698, found 337.0695 $[M+H]^+$.

C. elegans growth assay

A mixed-stage *C. elegans* N2 population was obtained by liquid culture (20 °C) according to standard methods [17]. It was then bleached to obtain an egg population with 1.5 mL 4M NaOH, 2.4 mL NaOCl, 2.1 mL water, washed three times, and allowed to hatch in 50 mL S-basal buffer at 20 °C overnight to obtain a synchronised L1 population. For the growth assay, 49 µL of S-complete buffer and 1 µL of DMSO or DMSO plus compound were added to each well of 96-well plates. 50 µL of a worm suspension (approximately 20 synchronised L1 worms, 1% w/v *E. coli* HB101 in S-complete buffer) were then added to each well. Plates were incubated at 20 °C before imaging 5 days later. Worm movement was stimulated by inserting and removing a 96-well PCR plate into/from the wells of the assay plate, and then whole plate 200 frame movies were recorded at 30 frames per second. Growth was quantified as a correlate of movement using the same automated system described earlier.

Cytotoxicity testing

The mouse rectal epithelial cell line CMT-93 (LGC Promochem, Teddington, United Kingdom) was used for these studies. The WST-8 and neutral red cytotoxicity assays were performed as described [12]. Briefly, cells were cultured with test compounds, chlorpromazine positive control or DMSO alone (final compound concentrations of 0 to 100 µM) for 72 hours. The WST-8 assay was then carried out using the Cell Counting Kit – 8 (Sigma Aldrich # 96992) with an incubation time of 2 hours. Following this assay, the medium was exchanged, and the ability of the cells to take up the dye neutral red (concentration 33 µg/mL, incubation time 2 hours was determined using a microplate reader (absorbance at 540 nm). Results were analysed using GraphPad Prism and fitted using a log-logistic model.

In vitro and *in vivo* establishment of infection

100 infective embryonated eggs were incubated in deionised water with 1% v/v DMSO or test compounds at a final concentration of 100 µM in 1% v/v DMSO for 14 days at room temperature in the dark. Eggs were then washed and resuspended in deionised water. For *in vitro* hatching assays 100 eggs were added to 1 mL of *E. coli* bacterial culture grown in LB broth overnight at 37 °C shaking at 200 rpm. Egg-bacterial cultures were incubated for 24 hours at 37 °C, 5% CO_2 and hatching determined following blinding by visual examination under a dissecting microscope. For *in vivo* hatching assays, 40 eggs were counted under a dissecting microscope and given to a SCID mouse in 200 µL water. At day 15 post-infection mice were culled and the number of worms present in the caecae and colon enumerated in a blinded manner.

Statistical analysis of *in vivo* establishment of infection data

The experiment was conducted in two ‘experimental batches’. For batch one there were 5 mice in each of the DMSO and **OX02926** groups. For batch two there were 9 mice in each of the DMSO and **OX02926** groups. The raw data (number of worms that established infection in each mouse) are shown separated by batch and treatment in the S1 Figure.

To analyse the data we used a two-way ANOVA (worm number ~ treatment * batch). This showed a significant effect of treatment [$F(1,24) = 8.520$, $P = 0.00752$]. It also showed a significant effect of batch [$F(1,24) = 10.956$, $P = 0.00294$]. There was no significant interaction between treatment and batch [$F(1,24) = 0.296$, $P = 0.59153$]. The significant effect of batch reflected that in both DMSO- and **OX02926**-treated groups, the number of worms that established infection was generally lower in mouse batch 1 than in batch 2 (S1 Figure). Variation in control worm establishment is commonplace in *Trichuris* infections due to natural variation in egg infectivity from a standardised egg number, but was within expected ranges. We therefore took the approach of normalising each data point by dividing by the mean of the DMSO-treated group for that batch. This gave the % batch normalised infection establishment.

We used a two-way ANOVA (% batch normalised infection establishment ~ treatment * batch) to analyse the data. There was a significant effect of treatment [$F(1,24) = 9.569$, $P = 0.00497$] but no effect of batch [$F(1,24) = 0.083$, $P = 0.77618$] or interaction [$F(1,24) = 0.083$ 0.77618]. We therefore conducted a post-hoc Tukey HSD test which showed that infection establishment in the OX02926-treated group was significantly different from the DMSO-treated control group ($P = 0.0050$).

Embryonation assay

One hundred unembryonated eggs were treated with a water, 1% v/v DMSO in water or test compounds at a final concentration of 100 µM (unless stated) with a final concentration of 1% v/v DMSO for 56 days in the dark at 26 °C. Images were collected on an Olympus BX63 upright microscope using a 60x / 1.42 PlanApo N (Oil) objective and captured and white-balanced using an DP80 camera (Olympus) in monochrome mode through CellSens Dimension v1.16 (Olympus). Images were then processed and analysed using Fiji [18].

Data availability

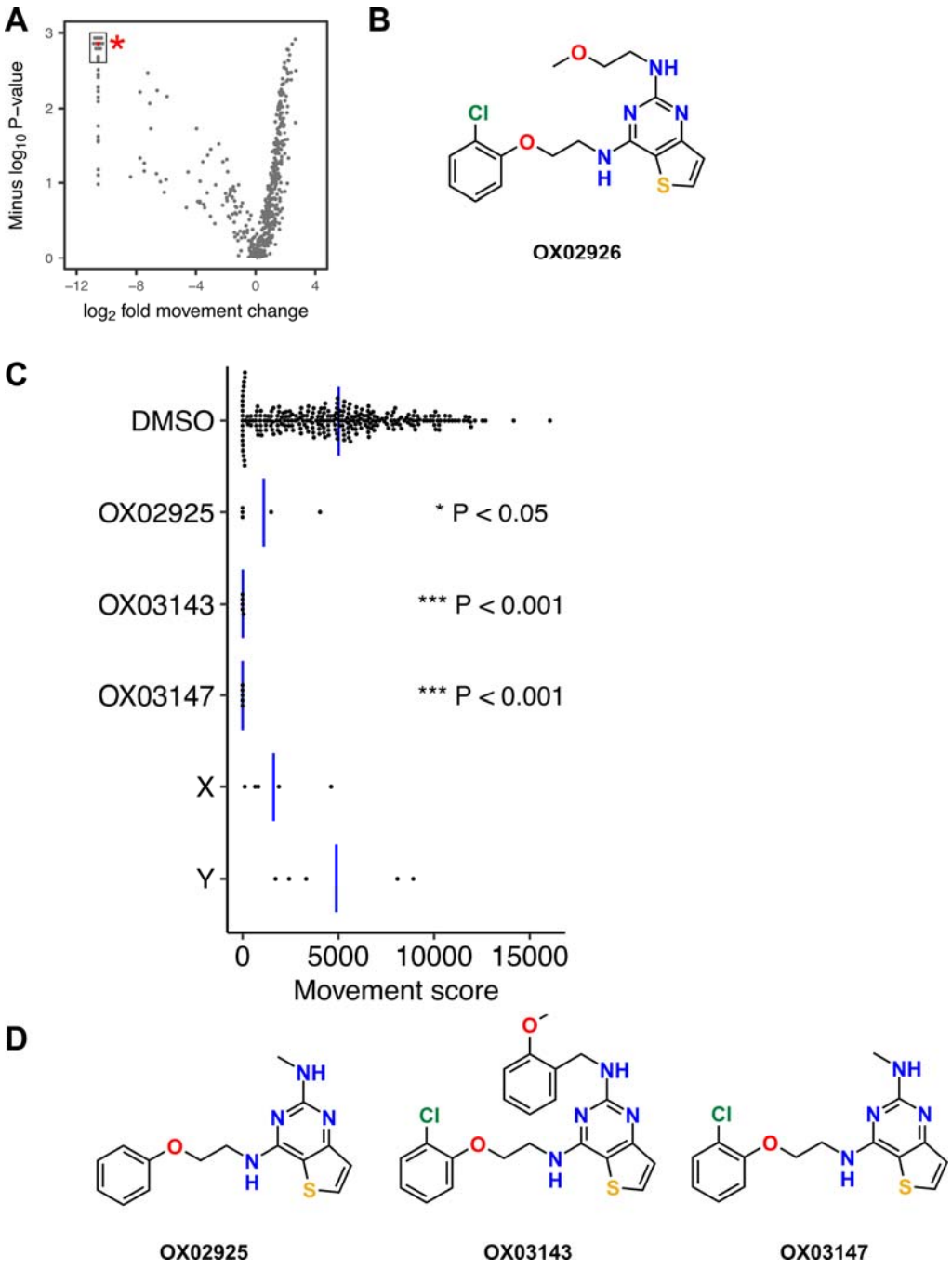
Structures of resynthesized compounds have been deposited in the PubChem database with CID 49790760, 49790669, 46948320 and 49778268 and SID 348479445, 348479446, 348479447 and 348479448. Assay results for resynthesized compounds have been deposited in the PubChem database with assay ID 1259352 and 1259353.

Results

Ex vivo T. muris adult motility screen

We have recently described a small molecule screen for new anthelmintics, which used reduction or loss of motility of adult *ex vivo T. muris* as an endpoint for screening [12]. This screen was designed to identify compounds active on *Trichuris* as existing drugs are notably less efficacious against this nematode, and it is comparatively evolutionary distant to nematodes typically screened in anthelmintic-discovery efforts, such as *H. contortus*, *M. incognita* and *C. elegans*. From this primary screen, we found 13 members of the dihydrobenzoxazepinone chemotype, which had not previously been shown to have anthelmintic activity.

In this report we describe the identification of a second new anthelmintic chemotype from this screen. A single 2,4-diaminothieno[3,2-*d*]pyrimidine (DATP) compound was found in the primary screen (Fig 1A). This has been given the identifier **OX02926**. We confirmed this activity in a secondary screen using the same source sample (DMSO solution containing 10 mM compound), and also tested a number of structurally-related compounds from our small molecule collection using the same assay (Fig 1C). This led to the identification of three further active molecules in this series **OX02925**, **OX03143** and **OX03147** (Fig 1D).



335

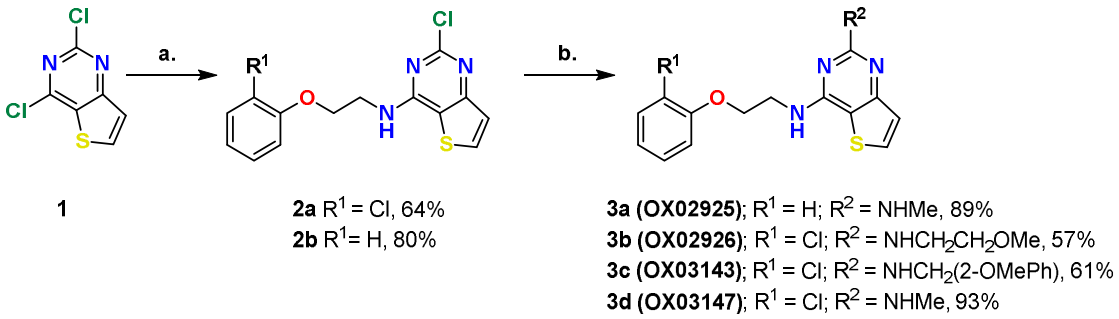
336 **Fig 1. Identification of a diaminothienopyrimidine series from an *ex vivo T. muris* motility**
337 **screen. (a)** Volcano plot of the primary screen conducted as in [12], with the single DATP hit
338 highlighted by a red asterix. Movement change and P-value compared to DMSO-only controls. *n*=4.
339 **(b)** Structure of the hit compound that was given the identifier **OX02926**. **(c)** Hit expansion by testing
340 of structurally-related compounds using library material. Significance was determined by a two-sided

Mann-Whitney test compared to DMSO-only controls, adjusted for multiple comparisons using the Bonferroni method (for test compounds n=5, each replicate on different assay plates, each point indicates one assay well). Blue bar indicates mean movement score. Compounds X (Pubchem CID: 49790326) and Y (Pubchem CID: 49795120) were not significantly active in this assay. **(d)** Structures and identifiers of additional active compounds from this class.

Resynthesis of active compounds

Having identified promising active DATPs from testing of DMSO solution samples of compounds, these were then resynthesised to obtain authentic, unambiguously characterised samples from which confirmatory screening could take place. Compound resynthesis is important since DMSO solution samples can degrade over time, and this often leads to so-called 'false positive' hits [19]. These compounds could be readily prepared in two steps from commercially available 2,4-dichlorothieno[3,2-*d*]pyrimidine **1**, via two sequential nucleophilic aromatic substitution reactions. Treatment of **1** with 2-(2-chlorophenoxy)ethylamine or 2-phenoxyethylamine gave exclusively monosubstitution affording **2a** and **2b** as a single regioisomer in 64% and 80% yield respectively. Aubsequent displacement reaction at C4 gave authentic samples of **OX02925**, **OX02926**, **OX03143** and **OX03147** in 57 – 91% yield (**Fig 2**).

358



1

2a R^1 = Cl, 64%
2b R^1 = H, 80%

3a (OX02925); R^1 = H; R^2 = NHMe, 89%
3b (OX02926); R^1 = Cl; R^2 = $NHCH_2CH_2OMe$, 57%
3c (OX03143); R^1 = Cl; R^2 = $NHCH_2$(2-OMePh), 61%
3d (OX03147); R^1 = Cl; R^2 = NHMe, 93%

359

360 **Fig 2. Synthetic route to putative hit compounds (a)** Substituted 2-phenoxyethan-1-amine
361 (1.0 equiv.), DIPEA (2.0 equiv.), 1,4-dioxane, 80 ^{o}C, 3 h. **(b)** Alkyl amine (10.0 equiv.), ^{i}PrOH,
362 100 ^{o}C, 16-24 h.

363 Activity of resynthesised diaminothienopyrimidines in the *T. muris ex vivo* adult motility assay
364 The resynthesized hits were then tested in this screen and a concentration-response curve constructed,
365 thereby confirming the anthelmintic activity of several examples of this structural class. (Fig 3,
366 Table 1).

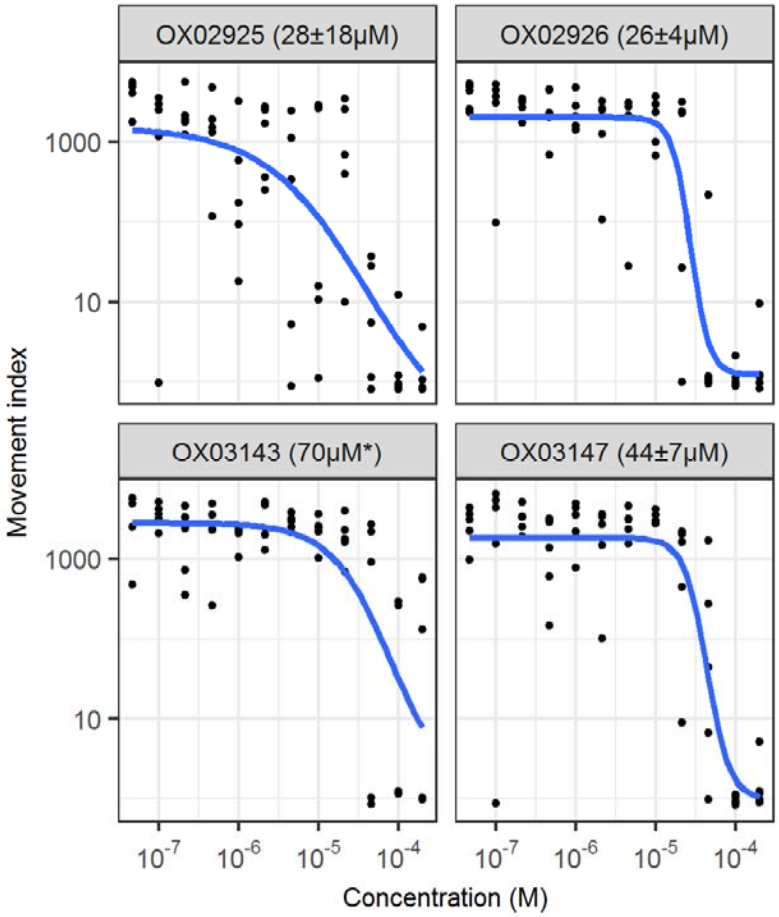


Fig 3. Concentration-response curves for resynthesized DATPs in the *T. muris ex vivo* adult motility assay. n=5 wells per concentration per compound, each replicate on a different 96-well plate, conducted on two experimental sessions using worms from different mice. Blue line indicates concentration-response curve fitted with the 4-factor log-logistic model using *drc* [16]. Figure in parenthesis indicates EC_{50} estimate ± standard error from this model. No confidence limit could be calculated for **OX03143.**

Chemical properties of the hit series and synthetic suitability for further development

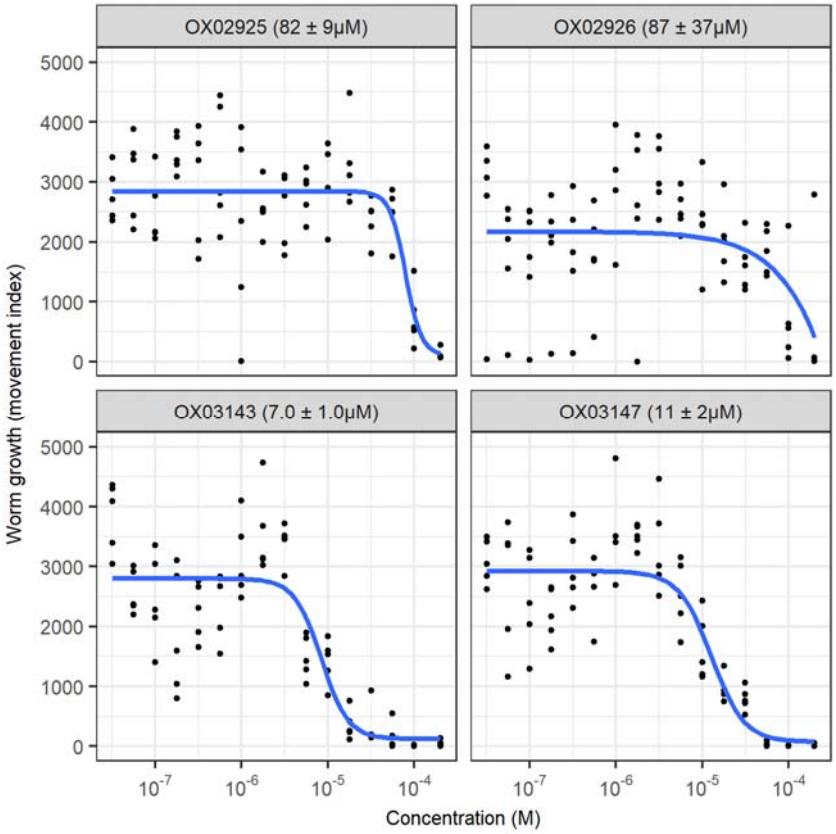
This class has 'lead-like' or 'drug-like' chemical properties [20], although it is important to note that in the contemporary medicinal chemistry literature this term is usually applied in the context of

imparting oral bioavailability characteristics (Table 1.). For agents targeting the gastrointestinal located *Trichuris*, minimal systemic exposure of the host is desirable and therefore it is critical to differentiate between the conventionally used terminology and parameters for 'drug-like' molecules, which affect solubility and permeability, and properties that would be relevant to agents targeting other body compartments. Recent literature has described this important caveat for non-peripheral CNS drugs [21], and indeed for anti-parasitic drug development [22]. Importantly, there is considerable scope for generating the large number of structural variants of the DATPs needed for the iterative improvement of compound properties during the downstream lead optimisation process.

Active diaminothienopyrimidines block *C. elegans* development

Although we are focused on developing an anthelmintic with improved efficacy over existing drugs against *Trichuris*, activity across the nematode phylum is valuable, particularly as efficacy against economically significant agricultural animal parasites would make further development more economically viable.

We therefore wanted to test the activity of the DATP chemotype against the clade V nematode *Caenorhabditis elegans.* Using a quantitative development assay to measure the growth of synchronised L1 stage worms, we tested varying concentrations of the compounds to determine the concentration-response effects. As shown in Fig 4, all four DATP compounds were active in this assay with EC_{50} values from 7 – 87 µM.

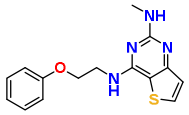
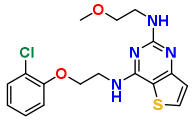
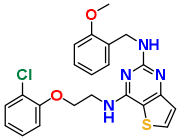
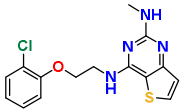
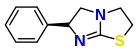
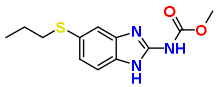
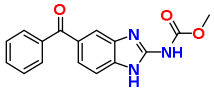
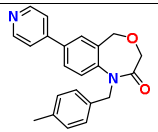


396

397 **Fig 4. Concentration-response curves for resynthesized DATPs in the *C. elegans* growth assay.**
398 n=5 wells per concentration per compound, each replicate on a different 96-well plate. Blue line
399 indicates concentration-response curve fitted with the 4-factor log-logistic model using *drc* [16].
400 Figure in parenthesis indicates EC_{50} estimate ± standard error from this model. No confidence limit
401 could be calculated for **OX03143**.

402 Interestingly, the DATPs display differing trends in activity between the *Trichuris* and *C. elegans*
403 assays. At this stage we do not know whether this reflects different potency at the target or different
404 patterns of drug access between the species, but the findings highlight the importance of screening
405 against *Trichuris* in the search for novel anthelmintic agents targeting whipworm. The data from each
406 of these assays as well as structural descriptors and Lipinski rule assessment for the four DATP
407 compounds and other anthelmintics are summarised in Table 1.

408 **Table 1. Properties and activities of resynthesized diaminothienopyrimidines, and other anthelmintics**

Compound	PubChem CID	Structure	EC_{50} (µM) *T. muris* paralysis assay	EC_{50} (µM) *C. elegans* growth assay	RMM	cLogP	HBA	HBD	tPSA (Å^2)	ROTB
		('Drug-like' guidelines)			*<500*	*<5*	*<10*	*<5*	*(<140)*	*(≤10)*
OX02925	49790760		28 ± 18	82 ± 9	300	2.5	5	2	87	6
OX02926	49790669		26 ± 4	82 ± 37	379	3.0	6	2	97	9
OX03143	46948320		70	7 ± 1	440	4.5	6	2	97	9
OX03147	49778268		44 ± 7	11 ± 2	344	3.1	5	2	87	6
Levamisole	26879		8 ± 3[a]	5 ± 1[a]	204	1.7	2	0	41	1
Albendazole	2082		> 800[b]	n.d.	249	2.3	6	2	76	5
Mebendazole	4030		>600[b]	1.1 ± 0.2[a]	295	2.7	6	2	84	4
OX02983	71447449		50 ± 13[c]	n.d.	344	2.7	4	0	42	3

409 RMM: relative molecule mass. HBA: number of hydrogen bond acceptors. HBD: number of hydrogen bond donors. tPSA: topological polar surface area,
410 calculated using DataWarrior [23]. ROTB: number of rotatable bonds. [a] Data from [15]. [b] Data from [24]. [c] Data from [12].

411 ## Assessment of the cytotoxicity of the diaminothienopyrimidine series

412 It was critical to ensure that this series showed minimal cytotoxicity towards mammalian cells, and
413 showed selective activity against the parasite. For example, gut cytotoxicity may result in the
414 compounds having too narrow a therapeutic window. Selected examples of the DATPs were assessed
415 for cytotoxicity using the mouse gut epithelial cell line CMT-93 (Table 2). Although, the DATPs
416 exhibited increased *in vitro* cytotoxicity in these assays compared to the previously reported DHB
417 series [12], an encouraging overall profile was exhibited for these early stage molecules. Furthermore,
418 the nematode cuticle often limits drug access which reduces target engagement by small drug-like
419 molecules [25,26]. This means that compound optimisation to improve uptake through the cuticle may
420 be a fruitful route to improved anti-nematode selectivity, as well as improving the cytotoxicity profile.

421 It is interesting to note that the activity against *Trichuris* did not correlate with cytotoxicity, with the
422 most cytotoxic compound (**OX03143**) showing the lowest activity in the *T. muris* adult paralysis
423 assay, by a factor of over 10-fold. This suggests that either anti-*Trichuris* activity is distinct from
424 cytotoxic action, or that differential drug access can be exploited to achieve differential host-parasite
425 activity. Either possibility is encouraging and suggests that continued exploration and iterative
426 improvement of the DATP structure might be anticipated to deliver a more potent anthelmintic with
427 acceptable host toxicity.

428

Compound	WST-8 EC_{50} (µM)	Neutral red EC_{50} (µM)	Adult *Trichuris* paralysis assay EC_{50} (µM)
OX02925	75 (48-124)	29 (19-43)	28
OX02926	43 (28-67)	21 (15-31)	26
OX03143	15 (9-26)	5 (3-7)	70
OX03147	37 (24-57)	21 (14-30)	44

429

430

431

432 **Table 2. Summary of the cytotoxicity in a mouse epithelial cell line of the DATP series.** Mouse
433 CMT-93 rectal epithelial cells were used for this assay. Maximum tested concentration was 100 µM.

434 n=8, error range (in parentheses) shows 95% confidence interval. EC_{50} values in the adult *Trichuris*
435 paralysis assay are shown for comparison.

436 ## Activity of diaminothienopyrimidines against the infective egg stages of *T. muris*

437 Developing novel anthelmintics to disrupt the *T. trichiura* life cycle at the egg stage represents an
438 exciting and complementary strategy to an oral therapy and is particularly attractive as *T. trichiura*
439 eggs are highly resistant to extreme temperature changes and ultraviolet radiation, thereby remaining
440 viable in the environment for many years [27]. We assessed whether the DATP derivatives were
441 capable of affecting either infection establishment or embryonation of eggs. We first explored whether
442 the compounds could alter the establishment of infection by soaking embryonated *T. muris* eggs in the
443 test compounds for 14 days, washing the eggs and then determining infectivity both *in vitro* and *in*
444 *vivo* (Fig 5A).

445 To determine effects on *in vitro* hatching, a protocol modified from that previously described [8] was
446 established whereby eggs were induced to hatch when incubated in a culture of *Escherichia coli* at 37
447 °C. The results are summarised in Fig 5B. Strikingly all DATPs were capable of significantly reducing
448 *in vitro* hatching compared to the DMSO control.

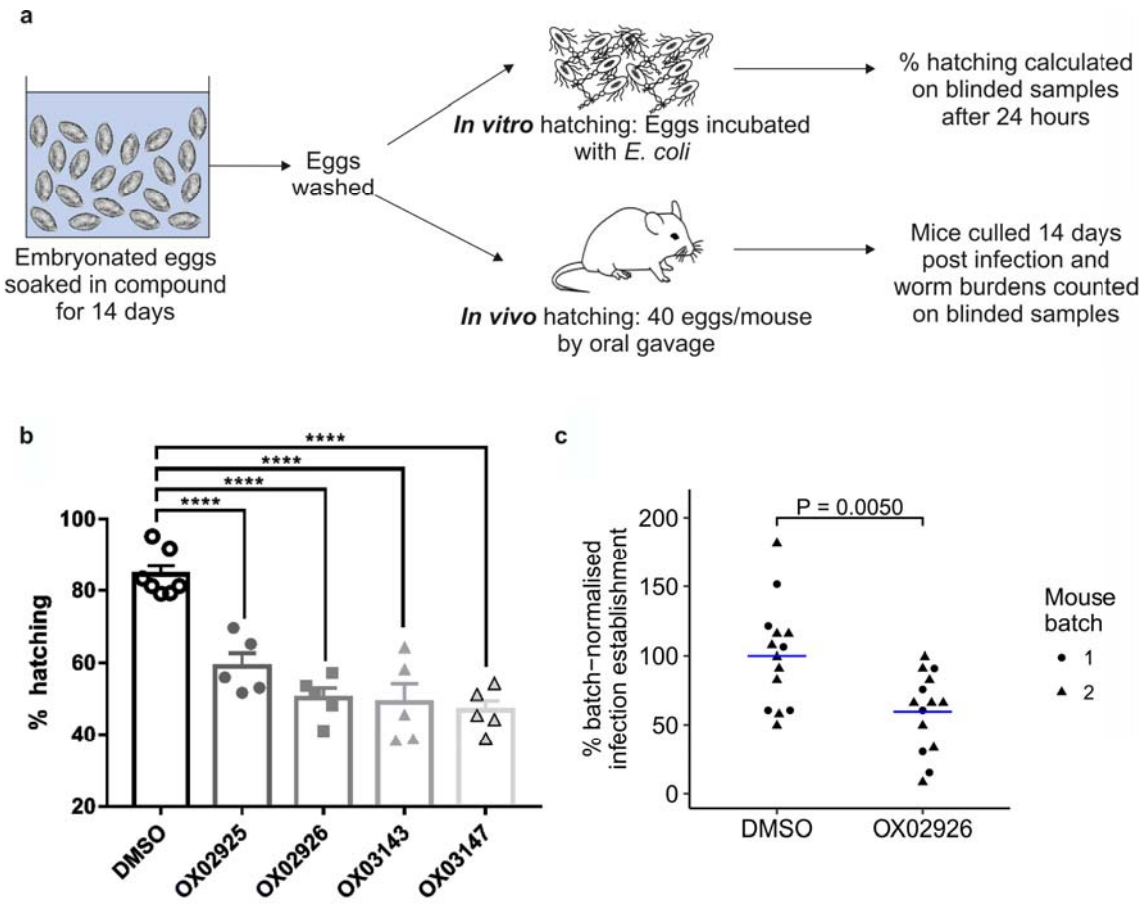
449 ## Diaminothienopyrimidines reduce the ability of *T. muris* eggs to infect mice

450 To extend this finding, we selected **OX02926** to test in an *in vivo* hatching and infection establishment
451 assay, as this compound showed both a significant decrease in *in vitro* hatching and a small standard
452 deviation between samples. The eggs were soaked as for the *in vitro* experiment and SCID mice were
453 infected with 40 treated eggs (**OX02926** or DMSO) by oral gavage. Egg infectivity was quantified at
454 day 15 post infection by culling the mice and counting the number of established worms in the gut.

455 This experiment was carried out in two batches and the raw data are shown in the S1 Figure. Because
456 variation in control worm establishment is commonplace in *Trichuris* infections due to natural
457 variation in egg infectivity from a standardised egg number, we took the approach of normalising data
458 for each batch relative to the mean of the DMSO-only control group for that batch. This allowed us to

459 determine the effects of **OX02926** treatment (a full statistical description is given in the Methods
460 section). The results are shown in Fig 5C. We used a two-way ANOVA (% batch normalised infection
461 establishment ~ treatment * batch) to analyse the data. There was a significant effect of treatment
462 [F(1,24) = 9.569, P = 0.00497] but no effect of batch [F(1,24) = 0.083, P = 0.77618] or interaction
463 [F(1,24) = 0.083 0.77618]. We therefore conducted a post-hoc Tukey HSD test which showed that
464 infection establishment in the **OX02926**-treated group was significantly different from the DMSO-
465 treated control group (P = 0.0050). **OX02926** was able to significantly reduce worm establishment *in*
466 *vivo* by an estimated 40%.

467



468

469 **Fig 5. *T. muris* eggs treated with diaminothienopyrimidines are less infective. (a)** Embryonated
470 eggs were soaked in compound for 14 days, washed in water and then used in either in vitro or in vivo

hatching assays. **(b)** Treatment with DATPs reduced the ability of embryonated eggs to hatch in *E. coli* bacterial suspension after 24 hours. A one-way ANOVA showed a significant difference between treatment groups ($F(5,26)=25.95$ $p<0.0001$) with a post-hoc Dunnett's compared to DMSO control (****= $p<0.0001$) $n=7$ (DMSO), $n=5$ (DATP compounds) **(c)** SCID mice were infected with 40 eggs and worm burden assessed at day 15 post infection. The experiment was carried out in two batches, with n=5 and n=9 mice respectively in each of the control and treatment groups. Data were normalised for each batch relative to the mean of the DMSO-only control group for that batch. Blue line indicates mean for each treatment group. A two-way ANOVA showed a significant effect of treatment [$F(1,24) = 9.569$, $P = 0.00497$] but no effect of batch [$F(1,24) = 0.083$, $P = 0.77618$] or interaction [$F(1,24) = 0.083$ 0.77618]. A post-hoc Tukey HSD test showed that the **OX02926**-treated group was significantly different from the DMSO control group ($P = 0.0050$).

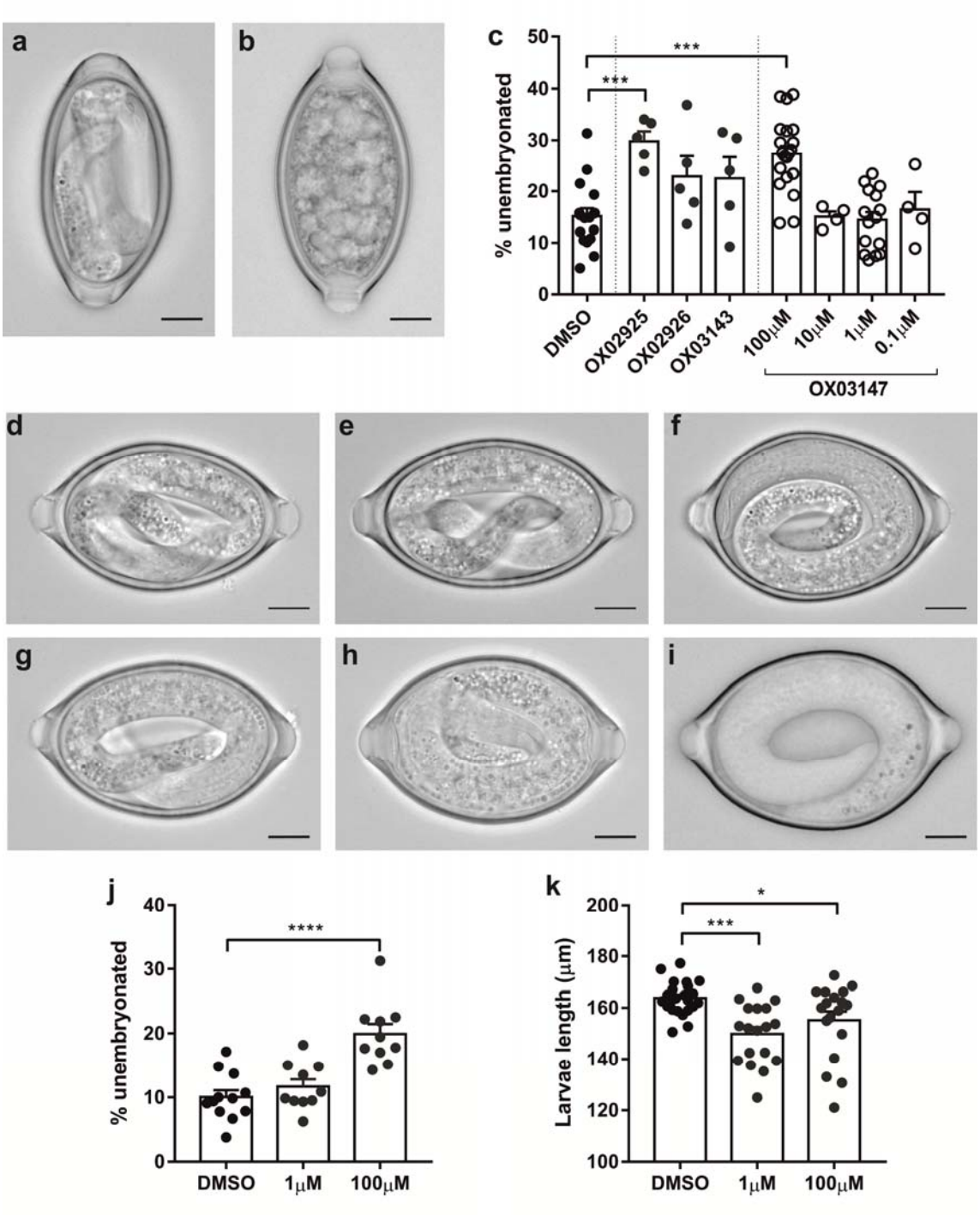
Activity of diaminothienopyrimidines against the embryonation of *T. muris* eggs

The ability of the DATPs to alter the embryonation of *T. muris* eggs was investigated by soaking unembryonated *T. muris* eggs collected overnight from live adult *T. muris* in the test compounds at 26 °C for the duration of the embryonation process (56-60 days). During embryonation the first larval stage of the parasite develops within the egg shell (Fig 6A) from a ball of cells (Fig 6B). Treatment with the DATPs **OX02925** and **OX03147** resulted in a significant increase in the percentage of unembryonated eggs present compared to the DMSO control (Fig 6D). Importantly, although the other DATPs did not alter the percentage of eggs unable to undergo the embryonation process, the larvae that developed were atypical (Fig 6D-I). These atypical larvae were morphologically altered with the granules present within the larvae appearing less distinct.

As **OX03147** had the clearest phenotype with a significant increase in the number of unembryonated eggs, a concentration response study was performed to determine if an effect could be seen at lower treatment doses. Additionally, we repeated the experiment at room temperature to allow for more

496 physiological conditions rather than the constant 26 °C utilised in the initial study to standardise
497 conditions across experiments. Although the increased number of unembryonated eggs was only
498 detected at the highest drug dose tested (100 µM) at both 26 °C and room temperature (Fig 6C, J)
499 striking effects on egg morphology was detectable at concentrations as low as 1 µM with significant
500 larvae stunting observed (Fig 6K).

501 To the known range of applications of DATPs in medicinal chemistry we can now add anthelmintic
502 activity. This study suggests they have significant potential for further development into dual-acting
503 therapeutic agents for both the reduction of *Trichuris* egg infectivity, and embryonation in the
504 environment. Thus, their actions on both the embryonated and unembryonated egg stages may enable
505 a break in the parasite lifecycle.



506

507 **Fig 6. Unembryonated *T. muris* eggs treated with diaminothienopyrimidines have altered**
508 **embryonation.** Unembryonated eggs were soaked in 100 μM compound (unless specified otherwise)
509 at 26 °C (unless specified otherwise) for the duration of the embryonation process (56-60 days) and
510 then embryonation determined and eggs imaged using an Olympus BX63 microscope. Scale bar

511 indicates 10 µm. **(a)** Typical embryonated egg and **(b)** unembryonated egg. **(c)** treatment with DATPs
512 increased the incidence of unembryonated eggs. Representative pictures of **(d)** DMSO, **(e) OX02925**,
513 **(f) OX02926**, **(g) OX03143** and **(h) OX03147** 100 µM and **(i) OX03147** 1 µM soaked *T. muris* eggs.
514 **(j)** Unembyronated eggs soaked in **OX03147** at room temperature for 56 days and embryonation
515 determined. **(k)** Unembyronated eggs soaked in **OX03147** at 26 °C for 56 days and larval length
516 calculated using ImageJ.

517

Discussion

Gastrointestinal nematode parasites remain a significant human health burden. Current anthelmintics lack efficacy and achieve low cure rates, threatening the targets set by the World Health Organisation for control of soil-transmitted helminths [2,28]. In particular, existing drugs have notably low efficacy against *T. trichiura*, the human whipworm. *T. trichiura* may be especially difficult to target as it inhabits the large intestine and is in part intracellular [29]. Thus, the metabolically active head end, the stichosome, is buried in the host epithelial cells lining the gut, affording some protection from orally delivered anthelmintics.

Diaminothienopyrimidines (DATPs), a new anthelmintic chemotype

We recently reported a small molecule screen for new anthelmintics targeting the gastro-intestinal (GI) nematode parasite *Trichuris muris* that identified the dihydrobenzoxazepinone (DHB) chemotype. The DHBs had not previously been ascribed anthelmintic activity [10]. Here, we describe a second class of novel anthelmintic, the diaminothienopyrimidines (DATPs). The potential for this early stage series is significant; the chemical synthesis of this series is facile and lends itself to iterative optimisation, will facilitate structural modifications aiming, for example, to increase local epithelial penetrance and hence improve efficacy during future development. Furthermore, this straightforward production imparts a favourable cost-economic aspect onto the series.

Activity against the egg stage of *T. muris*

In addition to activity against the adult stage of whipworm, the DATPs were also able to significantly reduce egg hatching, both *in vitro* and *in vivo*. These data are in keeping with members of the DHB series, which also were able to inhibit parasite egg hatching. However, unlike the DHB series, we identified members of the DATPs that also significantly reduced the percentage of eggs embryonating *ex vivo*, with other members of the DATP series appearing to disrupt the embryonation process, resulting in defects in embryonic elongation and abnormal egg shape. *Trichuris* egg embryonation occurs gradually and the mechanism by which it occurs is currently a poorly understood process. A detailed characterisation of the morphological changes which occur with the *Trichuris suis* egg during

544 embryonation has been described and other *Trichuris* species appear to undergo the same process.
545 Once the unembryonated, unsegmented eggs are deposited the two clear, nuclei-like areas move
546 together and fuse. Cellular division then begins, initially occurring asymmetrically with two
547 blastomeres of unequal size. The larger blastomere then divides again and then subsequently each
548 blastomere divides in two until a blastula forming of many small blastomeres develops. The initial
549 larval differentiation then occurs with the appearance of a motile cylindrical embryo, which gradually
550 turns into an infective larva with its characteristic oral spear. The fully developed larva is no longer
551 motile and is thought to be a L1 larva as no moult is observed within the egg [30]. The embryonation
552 process is temperature sensitive. The effect of temperature on egg embryonation has been
553 characterised in detail in recent years for *T. suis* eggs with the embryonation process accelerated at 30-
554 32 °C compared to 18 °C, with degeneration of the eggs rather than embryonation observed at higher
555 temperatures (40 °C). At low temperatures (5-10 °C) no embryonation occurs, however once these
556 eggs are then transferred to optimal embryonation temperatures normal embryonation proceeds [31].
557 Similar temperature sensitivity has been described for other *Trichuris* species including *Trichuris*
558 *trichiura* with different species embryonating with different kinetics [32,33]. More research is required
559 to understand the mechanisms behind this embryonation process, which may then allow an even more
560 targeted approach to breaking the life cycle.

561 Humans become infected with *Trichuris* via a faecal oral route. Adult parasites in the intestine shed
562 unembryonated eggs, which pass out with the faeces and embryonate in the external environment over
563 a period of five weeks. Parasite eggs are only infective if fully embryonated upon ingestion. Thus, the
564 ability of the DATPs to disrupt both embryonated egg hatching and the embryonation provides an
565 exciting alternative strategy, environmental control, to decrease *Trichuris* infection rates in the field
566 without the need to deliver anthelmintics to the infected host.

567 ## Other diaminothienopyrimidines – their applications and targets

568 Thienopyrimidines have received much interest in medicinal chemistry as they are bioisosteres for
569 purines, such as the nucleic acid components adenine and guanine. They are also related to

quinazolines, an important class of kinase inhibitors, including gefitinib and erlotinib, which act by recognizing the ATP-binding site of the enzyme [34]. Thieno[2,3-*d*]pyrimidines are a particularly important scaffold, with many reported examples of protein kinase inhibitors, as well as inhibitors of dihydrofolate reductase, kainite receptor agonists, and α_1-adrenoreceptor antagonists [35]. The thieno[3,2-*d*]pyrimidine scaffold, found in the compounds reported in this study, has also been investigated, leading to the identification of a series of phosphatidylinositol-3-kinase inhibitors [36]. A series of 2,4-diaminothieno[3,2-*d*]pyrimidines (the same core scaffold as the compounds reported in this study) have been described as orally active antimalarial agents [37], with activity in the low nanomolar range against *Plasmodium falciparum.* This series was later improved by systematic modification giving improved antimalarial activity, but unfortunately continued hERG inhibition [38]. A series of 2,4-diaminothieno[3,2-*d*]pyrimidines has also recently been reported as active against the endosymbiotic bacterium *Wolbachia*, with potential use against filarial nematodes [39]. In neither of these latter two cases is the molecular target of the compounds known.

Conclusions

In summary we report the discovery of a new class of anthelmintic, the DATPs, which possesses activity directed against adult stage *T. muris* parasites and the egg stage. Importantly, as a chemical series the DATPS are notable, since they are relatively facile to produce synthetically thereby presenting considerable scope for structural modifications to improve efficacy and deliver an optimised agent.

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Supporting information captions

S1 Figure. Raw data separated by batch for the *in vivo* hatching experiment. Each point indicates one mouse that has been infected with *T. muris* eggs that had been treated with deionised water plus 1% v/v DMSO (control) or deionised water plus 1% v/v DMSO and final concentration 100µM **OX02926** for 14 days. Blue line indicates mean for each treatment group.