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In vitro* and *in vivo* activity of 3-alkoxy-1,2-dioxolanes against *Schistosoma mansoni

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Abstract

Objectives

Compounds characterized by a peroxidic skeleton are an interesting starting point for antischistosomal drug discovery. Previously a series of 3-alkoxy-1,2-dioxolanes, which are chemically stable cyclic peroxides, demonstrated significant *in*

vitro activity against *Plasmodium falciparum*. We aimed to evaluate the potential of these compounds against *Schistosoma mansoni* and elucidate the roles of iron and peroxidic groups in activity.

Methods

Drugs were tested against juvenile and adult stages of *S. mansoni* *in vitro* and *in vivo*. Selected structures were assessed *in vitro* against schistosomes in the presence of additional iron sources. In addition, drugs were tested *in vitro* and *in vivo* against *Echinostoma caproni*, a non-blood-feeding intestinal fluke. Finally, the activity of non-peroxidic analogues was evaluated.

Results

Three dioxolanes displayed $IC_{50}s \leq 20.1 \mu M$ against adult schistosomes and values as low as $4.2 \mu M$ against newly transformed schistosomula. Nonetheless, only moderate, non-significant worm burden reductions were observed after treatment of mice harbouring adult infections. Drugs lacked activity against juvenile schistosomes *in vivo*. Two selected dioxolanes showed *in vitro* activity against *E. caproni* down to concentrations of 5 mg/L, but none of the compounds revealed *in vivo* activity. All tested non-peroxidic analogues lacked activity *in vitro* against both parasites.

Conclusions

Selected dioxolanes presented interesting *in vitro* activity, but low *in vivo* activities have to be overcome to identify a lead candidate. Although the inactivity of non-peroxidic analogues underlines the necessity of a peroxide functional group, incubation of adult schistosomes with additional iron sources did not alter activity, supporting an iron-independent mode of

activation.

Introduction

Schistosomiasis is a neglected tropical disease caused by trematode flatworms of the genus *Schistosoma*. Five species of schistosomes infect humans, with *Schistosoma haematobium*, *Schistosoma japonicum* and *Schistosoma mansoni* being responsible for the main burden of schistosomiasis.¹ Approximately 200 million people are affected by schistosomiasis, mainly in sub-Saharan Africa.² Praziquantel is currently the gold standard for the treatment of schistosome infections. Because of the threat of drug resistance and the limitations in the activity profile of praziquantel (the drug lacks activity against the juvenile schistosome stages), identification of potential drug candidates has a high priority.

The antischistosomal potential of the antimalarials artemisinin and its semisynthetic derivatives artesunate and artemether has been studied thoroughly in the past three decades, in in vitro and in vivo studies, and in clinical trials.^{3–5} Given the promising activity profile of the artemisinins, with particularly high activities observed against juvenile schistosomes, different groups of fully synthetic peroxides have been studied in vivo and in vitro in recent years.^{6,7} For example, the synthetic trioxolane OZ418 was recently introduced as a promising drug candidate showing high worm burden reductions (WBRs) of 80% and 86% against *S. mansoni* and *S. haematobium*, respectively.⁸

The high antimalarial activity of 1,2,4-trioxolanes triggered investigations with 1,2-dioxolanes, which are structurally analogous five-membered ring

peroxides offering enhanced chemical stability. However, the dioxolanes proved much less active than the corresponding 1,2,4-trioxolanes against *Plasmodium falciparum* in vitro and *Plasmodium berghei* in vivo.⁹ This reduction in activity has been attributed to a decreased tendency for scission of the alkoxy radicals derived from Fe(II) activation of the 1,2-dioxolane peroxide;¹⁰ β -scission to generate carbon radicals is considered important for the activity of peroxide antimalarials.¹¹ 3-Alkoxy-1,2-dioxolanes, which undergo activation by Fe(II) to generate oxygen-substituted alkoxy radicals closely related to the intermediates derived from trioxolanes, generate products indicative of efficient β -scission and have been shown to have promising antimalarial efficacy.¹⁰

To our knowledge the antischistosomal activity of the 3-alkoxy-1,2-dioxolanes has not been studied to date. In the present work 18 selected 3-alkoxy-1,2-dioxolanes were tested on *S. mansoni* in vitro and active candidates were followed up in vivo. To investigate whether the peroxide pharmacophore is an essential requirement for antischistosomal activity, non-peroxidic analogues of active compounds were synthesized and their antischistosomal potential was determined. In addition, the relationship between the parasite's haemoglobin consumption and the antischistosomal activity of compounds was studied in vitro by testing active compounds on the non-blood-feeding foodborne trematode *Echinostoma caproni* and evaluating the in vitro activity of active compounds under different incubation conditions, in media containing haemin, haemoglobin or red blood cells.

Materials and methods

Drugs

The 18 3-alkoxy-1,2-dioxolane substrates illustrated in Table 1 were prepared based upon methods described by Schiaffo et al.¹⁰ Two non-peroxidic analogues were prepared as illustrated in Figure S1 (available as Supplementary data at JAC Online).

Table 1.						
Chemical structures of investigated 3-alkoxy-1,2-dioxolanes and determined IC ₅₀ experiments against newly transformed schistosomula (NTS) and adult <i>S. mansoni</i> . <i>r</i> represents goodness of fit (conformity with $r \geq 0.85$)						
Compound				IC ₅₀ (μM) for 5, 60		
R ₁	R ₂	R ₃	R	NTS	r	adult
1	Me	Me	Me	31.1	0.9	13.9
2	Me	Bu	Me	7.5	1.0	12.4

[See full table](#)

Table 1. Chemical structures of investigated 3-alkoxy-1,2-dioxolanes and determined IC₅₀ values (mean of three experiments) against newly transformed schistosomula (NTS) and adult *S. mansoni* 72 h post-compound exposure; *r* represents goodness of fit (conformity with $r \geq 0.85$)

Animals and parasites

Animal studies were conducted following Swiss regulations on animal welfare at the Swiss Tropical and Public Health Institute (Basel, Switzerland, permission no. 2070). Three-week-old (weight ~14 g) female NMRI mice were purchased from Charles River (Sulzfeld, Germany) or Harlan Laboratories (Horst, The Netherlands). Before starting experiments, animals were allowed to adapt for 1 week under controlled conditions (temperature ~22°C; humidity ~50%; 12 h light and 12 h dark cycle; free access to rodent diet and water). Infection of mice with *S. mansoni* (Liberian strain) was performed subcutaneously by injection of 80–100 cercariae. Cercariae were harvested from infected intermediate host snails (*Biomphalaria glabrata*) by exposure to light for 3 h, following the standard procedures of our laboratory. For in vitro and in vivo studies with *E. caproni*, mice were infected intragastrically with 30 metacercariae harvested from infected *B. glabrata* snails.

In vitro screening

Preparation of NTS and adult schistosomes

NTS were obtained by mechanical transformation of *S. mansoni* cercariae.^{12,13} Cercariae were collected as described above. The schistosomula suspension was adjusted to a concentration of 100 NTS per 50 μ L with Medium 199 (Invitrogen, Carlsbad, CA, USA) supplemented with 5% heat-inactivated fetal calf serum (iFCS), 100 U/mL penicillin and 100 mg/L streptomycin (Invitrogen). To ensure completed conversion from cercariae to NTS, suspensions were incubated at 37°C in an atmosphere of 5% CO₂ in ambient air for a minimum of 12–24 h until use.¹⁴

Adult flukes were harvested from hepatic portal veins and mesenteric veins of infected NMRI mice (7–8 weeks post-infection) following standard procedures.⁶ Schistosomes were placed in RPMI 1640 culture medium supplemented with 5% iFCS, 100 U/mL penicillin and 100 mg/L streptomycin at 37°C in an atmosphere of 5% CO₂ until use.

Preparation of adult *E. caproni*

Infected mice were killed 2 weeks post-infection. Trematodes were harvested from the excised small intestine and placed in RPMI medium supplemented with 100 U/mL penicillin, 100 mg/L streptomycin and 1% α -D-glucose (Sigma Aldrich, St Louis, MO, USA). Flukes were maintained at 37°C in an atmosphere of 5% CO₂ in ambient air until use.

Drug susceptibility assays with NTS

Drug dilution series with concentrations ranging from 0.37 to 90 mg/L (0.37, 1.1, 3.3, 10, 30, 90 mg/L) were prepared in 96-well flat-bottom plates (BD Falcon, USA) using supplemented medium (with iFCS and antibiotics).

Prepared NTS suspension containing 100 NTS per 50 μ L was added to each well to yield a total volume of 250 μ L per well. The highest DMSO concentration (1.1%) used, diluted in Medium 199, served as control. Plates were incubated at 37°C in an atmosphere of 5% CO₂. NTS were evaluated by microscopic readout (Carl Zeiss, Germany, magnification \times 80) with regard to death, changes in motility, viability and morphological alterations 24, 48 and 72 h post-drug exposure. As described previously, drug effects were evaluated using a viability scale.^{[12,13](#)} Parasite fitness, morphology and motility were classified with scores ranging from 3 (normal activity, no morphological changes) to 0 (all worms dead). Duplicate examinations were performed for each concentration and experiments were repeated at least three times. IC₅₀ values of the investigated drugs based on motility scale values obtained at the 72 h timepoint were determined using CompuSyn software (Version 3.0.1, 2007; ComboSyn, Inc.).

Drug susceptibility assay with adult schistosomes

In vitro screening on adult flukes was performed in 24-well flat-bottom plates (BD Falcon, USA). Supplemented RPMI 1640 medium (with iFCS and antibiotics) and drug stock solutions (10 mg/mL) were used to obtain final test concentrations of 1–90 mg/mL (1.1, 3.3, 10, 30, 90 mg/L) in wells with a final volume of 1.4 mL. Finally, three schistosomes of both sexes were added to each well. The highest concentration of DMSO (0.3%) in medium served as control. Twenty-four, 48 and 72 h post-drug exposure, phenotypes were monitored using the motility scale described by Ramirez et al.^{[15](#)} and an inverse microscope (Carl Zeiss, Germany, magnification \times 80). Experiments were performed three times. IC₅₀ values were calculated with CompuSyn software as described above for NTS (Version 3.0.1, 2007; ComboSyn, Inc.).

Drug susceptibility assay of adult *S. mansoni* in the presence of haemin, haemoglobin or red blood cells

Lead candidates were incubated as described above, but using different RPMI culture medium conditions. A haemin solution (1.5 mM) was prepared as follows: 50 mg haemin chloride (Fluka Analytical, The Netherlands) was dissolved in 10 mL of 0.1 M NaOH, 0.5 mL of 1 M HCl and 39.5 mL of PBS (pH=7.4). The haemoglobin solution (0.23 mM) was prepared using 750 mg haemoglobin from bovine blood (Sigma Aldrich, USA) dissolved in the same amounts of NaOH, HCl and PBS as used above. Finally, supplemented RPMI media were prepared by adding 8% haemin solution, 10% haemoglobin solution or 2% red blood cells from red blood cell concentrate (blood group A Rhesus positive) to final concentrations in well plates of 120 μ M for haemin, 23 μ M for haemoglobin or 2% for red blood cells. At timepoints 24, 48 and 72 h post-exposure, phenotypes were monitored using the motility scale as described above using an inverse microscope (Carl Zeiss, Germany, magnification \times 80) and data were compared between various incubation conditions.¹⁵

Isothermal microcalorimetry (IMC) drug assay with adult *S. mansoni*

Two non-peroxidic analogues (compounds 19, 20) and one selected dioxolane (compound 16) were further characterized using IMC as described by Manneck et al.¹⁶ Briefly, heat production and motility (derived from noise amplitudes) of schistosomes were measured using a 48-channel microcalorimeter (model TAM 48; TA Instruments, New Castle, DE, USA) over a period of 5 days. Samples were prepared in glass ampoules with 2900 μ L of medium (supplemented RPMI 1640) containing four adult worms. Pre-warmed (37°C) ampoules were placed in channels and equilibration was performed for 12 h until a stable signal was observed. Drug suspensions

(concentration of 900 mg/L) in supplemented medium (volume 100 μ L) were injected, using 1 mL syringes (BD Plastipak, Becton Dickinson S.A., Madrid, Spain), to reach the final concentration of 30 mg/L per ampoule. Ampoules with dead worms served as the negative control and ampoules with worms treated with the highest concentration of DMSO (0.3%) served as the positive control. Heat flow was recorded as 1 data point per 1 min over at least 120 h. Tests at each concentration were performed three times.

Drug susceptibility assay with adult *E. caproni*

Assays were prepared in 24-well flat-bottom plates (Costar). Drug dilutions were prepared with drug stock solutions and supplemented RPMI medium (with antibiotics and glucose) to obtain final drug concentrations of 5–100 mg/L (5, 10, 50, 100 mg/L) in a total volume of 2 mL per well. Six to nine trematodes were used (one or two worms per well) for each experimental group. The highest concentration of DMSO (1%) served as control. Plates were incubated at 37°C in an atmosphere of 5% CO₂. Twenty-four, 48 and 72 h post-drug exposure, phenotypes and mortality of worms were monitored as described elsewhere.^{[12](#)}

In vivo screening

Studies with *S. mansoni*

Groups of four infected NMRI mice characterized by a patent schistosome infection (49 days post-infection) or a juvenile *Schistosoma* infection (21 days post-infection) were treated orally with the test drug using single oral doses of 400 mg compound per kg body weight. Seven to nine untreated mice served as controls. Animals harbouring an adult *Schistosoma* infection were killed by the CO₂ method 14 days post-treatment, and mice treated at the juvenile infection stage were sacrificed 4 weeks post-treatment. Mice

were then dissected and worms sexed and counted.⁶ Worm burdens of treated mice were compared with those of untreated animals and reductions of worm burden calculated.

Studies with *E. caproni*

Four NMRI mice were treated intragastrically with 400 mg/kg of test compounds 2 weeks post-infection with *E. caproni*. Four mice were left untreated and served as controls. One week post-treatment, mice were euthanized with CO₂. At necropsy, the intestines were removed from the pylorus to the ileocaecal valve, placed in a Petri dish and opened longitudinally. All *E. caproni* worms were removed and counted.

Statistics

Parasite motility of treated and untreated NTS and adult trematodes was calculated as mean (\pm SD) using Microsoft Excel software. Motility data obtained from experiments with various media containing iron sources were compared using the Mann–Whitney test (considered significant at $P \leq 0.05$). IC₅₀ values were determined using the CompuSyn software (Version 3.0.1, 2007; ComboSyn, Inc.). For the comparison of IC₅₀ values we used the Kruskal–Wallis test (considered significant at $P \leq 0.05$). The Kruskal–Wallis test was also used for in vivo studies, comparing the medians of the responses between the treatment and control groups. A difference in median was considered to be significant at a significance level of 5% (StatsDirect statistical software, version 2.7.2.; StatsDirect Ltd, UK). Noise amplitudes and heat flows observed in calorimetric in vitro assays with adult *S. mansoni* were analysed using R software and Microsoft Excel. As described by Manneck et al.,¹⁷ noise amplitude values follow an exponential decay. Endpoints of worm motility were determined by the intersection of the

sample amplitude curve with the background signal noise of dead worms.

Results

In vitro screening against *S. mansoni*

In a first step, 14 3-alkoxy-1,2-dioxolanes were studied against adult *S. mansoni* in vitro. Three of the compounds (1, 2 and 3) demonstrated good antischistosomal activity with IC₅₀s of 11.9, 12.4 and 20.1 µM, respectively, against adult flukes. The remaining 11 substances revealed only minor activity (IC₅₀s between 49.2 and 283.3 µM) or lacked activity (compound 14). Good activities were observed against the juvenile schistosome stage (NTS) for compounds 2 (IC₅₀ 7.5 µM) and 3 (IC₅₀ 4.2 µM). Moderate activity was detected for compounds 1 (IC₅₀ 31.1 µM), 5 (IC₅₀ 17.0 µM) and 6 (IC₅₀ 35.9 µM) against NTS. Finally, only minor activity was recorded for the remaining nine compounds against NTS (IC₅₀ 42.6–102.5 µM). In vitro findings are summarized in Table [1](#). For comparison, activities of standard antischistosomal drugs, praziquantel and artesunate, are also shown in Table [1](#).

Influence of haemin, haemoglobin or red blood cells on in vitro antischistosomal activity

Incubation of adult schistosomes with various concentrations (1.1, 3.3, 10, 30 mg/L) of the three active alkoxydioxolanes (1–3) in supplemented media containing haemin, haemoglobin or red blood cells showed no significant differences in activity. The motilities recorded 72 h post-exposure of *S. mansoni* with compound 1 at different concentrations did not vary among the different media tested (Figure [1](#)). Slightly higher, though not significant ($P > 0.05$) activities were detected for compounds 2 and 3 when incubated in

the presence of haemin or haemoglobin. In the presence of these media all worms had died 72 h post-exposure to the tested compounds at a concentration of 10 mg/L and 30 mg/L.



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Figure 1. Motility of adult schistosomes 72 h post-treatment with various concentrations (1.1, 3.3, 10 and 30 mg/L) of compounds 1, 2 or 3 in four different incubation settings. (a) Standard incubation with supplemented RPMI. (b) Addition of 2% red blood cells from red blood cell concentrate. (c) Addition of 120 μ M haemin. (d) Addition of 23 μ M haemoglobin.

In vivo activity of selected alkoxydioxolanes against *S. mansoni*

The three lead structures 1–3 identified by prior in vitro screening, were tested in a juvenile as well as an adult *S. mansoni* infection mouse model (Table 2). All studied alkoxydioxolanes lacked in vivo activity against juvenile *S. mansoni* (Table 2; WBRs 0%–4%). However, moderate, non-significant activities were observed with compounds 1 and 2 against adult *S. mansoni* with WBRs of 42.5% and 37.0%, respectively. Compound 3 showed only low activity against adult *S. mansoni* in vivo with a WBR of 15.1%. Dead worms were detected in mouse livers after treatment of adult infections with compounds 1, 2 and 3. The presence of a patent schistosoma infection in treated animals was confirmed by observing granulous tissue and *Schistosoma* eggs within all livers.

Table 2.
In vivo activity following a single oral dose of 400 mg/kg of selected 3-alkoxy-1,2-dioxolanes in mice harbouring juvenile or adult *S. mansoni*

Group	No. of mice investigated	No. of mice that died	No. of mice cured	TWR (%)
Control	8	0	0	—
Juvenile infection				
1	4	0	0	0
2	4	0	0	4.1
3	4	0	0	0
Adult infection				
1	4	0	0	42.5
2	4	0	0	32.0
3	4	0	0	15.1

[See full table](#)

Table 2. *In vivo* activity following a single oral dose of 400 mg/kg of selected 3-alkoxy-1,2-dioxolanes in mice harbouring juvenile or adult *S. mansoni*

In vitro and in vivo activity of modified lead dioxolanes against *S. mansoni*

Given the low in vivo activity of the three test drugs, we were motivated to investigate four additional chemically related alkoxydioxolanes in vitro against NTS and adult schistosomes, followed by in vivo studies on a patent *S. mansoni* infection. All four compounds (15–18) showed very high activities against NTS, represented by low IC₅₀ values (2.7–4.8 μ M) (summarized in Table 1). However, the four drugs revealed only low activities against adult schistosomes in vitro, with IC₅₀s between 49.4 and 109.3 μ M. Moderate, but non-significant, in vivo WBRs of 32.0% and 21.3% were achieved with compounds 15 and 17, respectively. Low activities with WBRs of 12.0% and 16.4% were observed with compounds 16 and 18, respectively (summarized in Table 3).

Table 3.
In vivo activity following a single oral dose of 400 mg/kg of selected 3-alkoxy-1,2-dioxolanes in mice harbouring adult *S. mansoni*

Group	No. of mice investigated	No. of mice that died	No. of mice cured	TWR (%)
Control ^a 1	8	0	0	—
Control ^b 2	8	0	0	—
15 ^a 3	4	1	0	32.0
16 ^a 4	4	1	0	12.0
17 ^a 5	4	1	0	21.3
18 ^b 6	4	0	0	16.4

TWR, total worm burden reduction; FWBR, female worm burden reduction.
^aVersus control.
^bVersus control.

[See full table](#)

Table 3. *In vivo* activity following a single oral dose of 400 mg/kg of selected 3-alkoxy-1,2-dioxolanes in mice harbouring adult *S. mansoni*

In vitro and in vivo effect against *E. caproni*

Lead structures 1–3 as well as the four related structures (15–18) were tested in vitro on freshly harvested *E. caproni*. Data are summarized in Table 4. Six of seven compounds (1, 3, 15–18) showed 100% worm mortality 24 h post-drug exposure at a concentration of 50 mg/L. Two of the compounds (16 and 17) killed all worms 24 h post-incubation at a 5-fold lower concentration of 10 mg/L. Incubation of adult *E. caproni* with three spirocyclohexyl compounds (3, 16 and 17) at 5 mg/L for 72 h resulted in death of all worms. Compounds 15–17 were followed up in vivo. Treatment of *E. caproni*-infected mice with a single oral dose of 400 mg/kg of compound 15 resulted in a low WBR of 17.4%. Compounds 16 and 17 lacked in vivo activity (Table 5).

Table 4.
in vitro mortality of *E. caproni* worms at timepoints 24, 48 and 72 h post-drug treatment with selected compounds

Drug	Drug concentration (mg/L)	No. of worms observed	Percentage of worms		n
			0 h	24 h	
Control	–	20	0	0	0
1	100	8	0	100	0
	50	8	0	100	0
	10	7	0	43	1
	5	8	0	25	7
2	100	6	0	100	0
	50	6	0	0	1
	10	6	0	17	0

[See full table](#)

Table 4. *In vitro* mortality of *E. caproni* worms at timepoints 24, 48 and 72 h post-drug treatment with selected compounds

Table 5.
in vivo activity following a single oral dose of 400 mg/kg of selected 3-alkoxy-1,2-dioxolanes against *E. caproni* in mice

Group	No. of mice investigated	No. of mice cured	Worms	TWR (%)	P value
Control	4	0	23.0/100	–	–
15	4	0	19.0/17.2	17.4	0.2
16	4	0	27.0/14.0	0.0	0.2
17	4	0	23.0/17.0	0.0	0.5

TWR, total worm burden reduction.

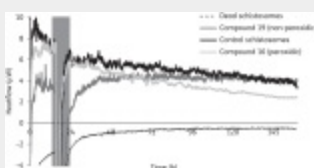
[See full table](#)

Table 5. *In vivo* activity following a single oral dose of 400 mg/kg of selected 3-alkoxy-1,2-dioxolanes against *E. caproni* in mice

In vitro activity of non-peroxidic analogues

To elucidate the role and necessity of the peroxide core of the alkoxydioxolanes for trematocidal activity we tested the in vitro activity of two alkoxy-substituted tetrahydrofurans (19, 20) prepared as non-peroxidic

analogues of the alkoxydioxolanes. Both derivatives lacked activity at concentrations of 30 and 90 mg/L against *S. mansoni*. Also, *E. caproni* was not affected at 50 and 100 mg/L. No effect against adult *S. mansoni* could be observed by microscopic examination 72 h post-treatment as well as by IMC 6 days after treatment. According to IMC, no loss of motility was detected for either non-peroxidic compound over an incubation period of 6 days (concentration 30 mg/L). For comparison, treatment of adult *S. mansoni* with 30 mg/L of the peroxidic analogue of compound 19 (compound 16) revealed a reduction in heat flow and complete loss of motility was detected 90 h post-exposure (Figure 2).



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Figure 2. Course of heat flow (μW) over time (h) after treatment of schistosomes with compound 19 (non-peroxidic) or compound 16 (peroxidic). Control schistosomes correspond to schistosomes treated with DMSO at the same concentration as used for drugs (0.3%). Amplitudes of curves represent the motility of schistosomes.

Discussion

The antischistosomal activity of semisynthetic artemisinins, frequently used in malaria treatment, synthetic trioxolanes and hybrid molecules of quinines and trioxanes has been well described.^{7,8} Compounds characterized by a peroxidic skeleton are therefore an interesting starting point for antischistosomal drug discovery. Hence, we were interested in elucidating the antischistosomal potential of recently introduced alkoxydioxolanes as well as their structural needs for activity against schistosomes.¹⁰

Three of 14 compounds tested (compounds 1–3) showed promising in vitro

activity against adult *S. mansoni* flukes. Two of these compounds (2 and 3) also revealed very good efficacy against the juvenile stage (NTS) *in vitro*. The antischistosomal *in vitro* activity seems to be enhanced by the presence of a bulky substituent at C3, since the three lead compounds all feature a large alkoxide side chain at C3. The remaining non-active 11 compounds do not display this feature. This finding is in accordance with observations reported by Schiaffo et al.¹⁰ on the antimalarial structure–activity relationship of similar compounds. These studies revealed that antimalarial activity is enhanced by a spirocyclohexyl group at C5/C5' and by the presence of a steric bulk at C3. However, for antischistosomal activity it does not seem to matter whether substitution at C5/C5' is a dimethyl (compound 2) or spirocyclohexyl (compound 3) group. On the other hand, it is interesting to note that, with regard to *E. caproni*, the three most active compounds (3, 16 and 17) all display spirocyclohexyl units.

In our *in vivo* studies we observed only moderate, non-significant activities of alkoxydioxolanes in *S. mansoni*-infected NMRI mice. Compound 1 showed the highest *in vivo* activity against adult *S. mansoni*, achieving a total WBR of 42.5% and a female WBR of 47.1%. In contrast to results reported for artemisinins, surprisingly low WBRs were observed against juvenile *S. mansoni* harboured in mice.¹⁸ A recent study conducted with a library of dioxolanes revealed that the majority of the compounds tested against rat and human microsomes were metabolized rapidly. It was concluded that significant optimization of the groups attached to the dioxolane core is needed before a viable candidate for drug development could be identified.¹⁹ Hence, it is likely that the alkoxydioxolanes tested in this study also exhibit bioavailability problems which can likely play a role in limiting *in vivo* activities.

In the present work we also studied the activity of alkoxydioxolanes in the presence of various additional iron sources, since haemoglobin metabolism, the potential target of these drugs, is a common feature of both *Schistosoma* and *Plasmodium* spp.²⁰ Earlier studies investigated the relationship between Fe(II) reactivity, the efficiency of haem alkylation and antimalarial activity for various peroxides in vitro. The authors stated that Fe(II) reactivity for the tested peroxide heterocycles is a necessary, but insufficient, property of antimalarial peroxides,²¹ and the alkoxydioxolanes have been shown to undergo cleavage to alkoxy radicals in the presence of iron(II).¹⁰ Interestingly, we did not observe significant differences in susceptibility of the tested agents in the different iron-source-containing media. This finding is in contrast to the haemin-dependent antischistosomal in vitro effect of the trioxolane OZ78 on *S. mansoni* and *S. japonicum*, whereas similar haemin-independent activity was described for OZ209.^{6,22} Similarly, it was recently shown that the antimalarial arylmethanol mefloquine, a drug class also described to interfere with haemoglobin degradation in *Plasmodium*, revealed a 57-fold lower IC₅₀ in the presence of haemoglobin against adult *S. mansoni* in vitro.²³ Our results suggest that the alkoxydioxolanes possess an iron-independent mechanism of action on schistosomes in vitro. This discovery is supported by the observed high in vitro activities of three compounds (3, 16 and 17) at concentrations as low as 5 mg/L against the non-haematophagous intestinal fluke *E. caproni*.

Nonetheless, the results with the isosteric compounds that lack a peroxide functional group underline the necessity of the peroxidic core for trematocidal activity. Both compounds lacked in vitro activity against adult *S. mansoni* and *E. caproni*. Similar results were recently demonstrated in studies with the liver fluke *Fasciola hepatica*. While OZ78 has excellent in

vitro and in vivo activity against *F. hepatica*, its non-peroxidic analogue failed to show an effect against the fluke.²⁴ The peroxidic feature seems therefore to play a role in the iron-independent mode of action. The basis for the iron-independent activity of the alkoxydioxolanes is unclear. These molecules, like all peroxides, are oxidants, and in principle capable of reaction with strongly nucleophilic or reducing agents. Alternatively, it is possible that the alkoxydioxolanes undergo activation via acid-catalysed ring opening of the peroxyacetal core to generate a more reactive 3-hydroperoxyketone; a similar model has been proposed to account for the antimalarial activity of artemisinin.²⁵

In conclusion, we have demonstrated that a number of alkoxydioxolanes are characterized by good in vitro antischistosomal activity and non-significant in vivo effects on *S. mansoni*, with compound 1 being the most promising candidate. Similarities, but also differences, exist between antimalarial and antischistosomal activity of alkoxydioxolanes. The peroxidic bond is essential to antischistosomal activity, but activation of the molecules seems to be independent of iron. The low in vivo activity of this drug class, which may result from limited bioavailability, represents a challenge that would need to be overcome in order to identify an antischistosomal lead candidate.

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Transparency declarations

None to declare.

Supplementary Material

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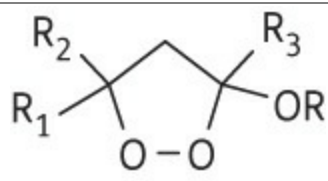
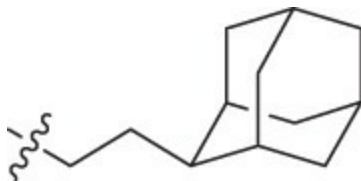
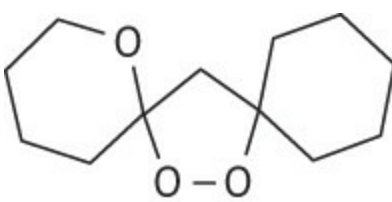
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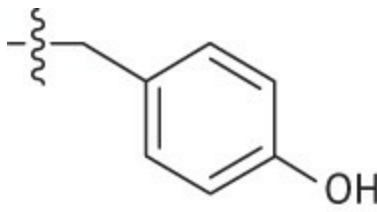
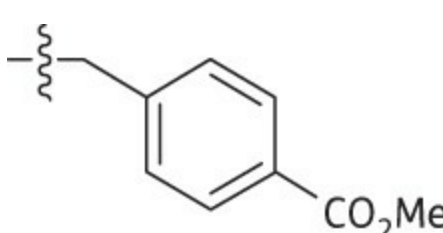
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Table 1.

Chemical structures of investigated 3-alkoxy-1,2-dioxolanes and determined IC₅₀ values (mean of three experiments) against newly transformed schistosomula (NTS) and adult *S. mansoni* 72 h post-compound exposure; *r* represents goodness of fit (conformity with $r \geq 0.85$)

Compound					IC ₅₀ (
	R ₁	R ₂	R ₃	R	NTS
1	Me	Me	Me		31.1
2	Me	Bu	Me	CH ₂ CH ₂ Ph	7.5
3	-(CH ₂) ₅ -	CH ₂ CH ₂ Ph	CH ₂ CH ₂ Ph	CH ₂ CH ₂ Ph	4.2
4	Me	Me	CH ₂ Ph	Me	101.0
5					17.0
6	Me	Me	Me	5,6-epoxyhexyl	35.9
7	Me	Me	Me	CH ₂ CH ₂ CN	89.2
8	-(CH ₂) ₅ -	Me		CH(OH)CH ₂ OH	90.9

9	Me	Me	Me	$(\text{CH}_2)_9\text{CO}_2\text{Me}$	89.7
10	Me	Me	Me	$\text{CH}_2\text{CH}_2\text{CO}_2\text{Me}$	76.0
11	Me	Me	Me	$\text{CH}_2\text{CH}_2\text{OMe}$	69.2
12	Me	Me	Me	$\text{CH}_2\text{CH}_2\text{CH}_2\text{OH}$	42.6
13	Me	Me	Me	$(\text{CH}_2)_4\text{CO}_2\text{Me}$	59.8
14	Me	Me	Me	$\text{CH}(\text{OH})\text{CH}_2\text{OH}$	102.5
15	Me	Me	Me	$\text{CH}_2\text{CH}_2\text{Ph}$	2.7
16	$-(\text{CH}_2)_5-$	Me		$\text{CH}_2\text{CH}_2\text{Ph}$	2.8
17	$-(\text{CH}_2)_5-$	Me			4.1
18	Me	Me	Me		4.8
Praziquantel					2.2
Artesunate					5.0

^aAs described by Keiser et al.²⁶

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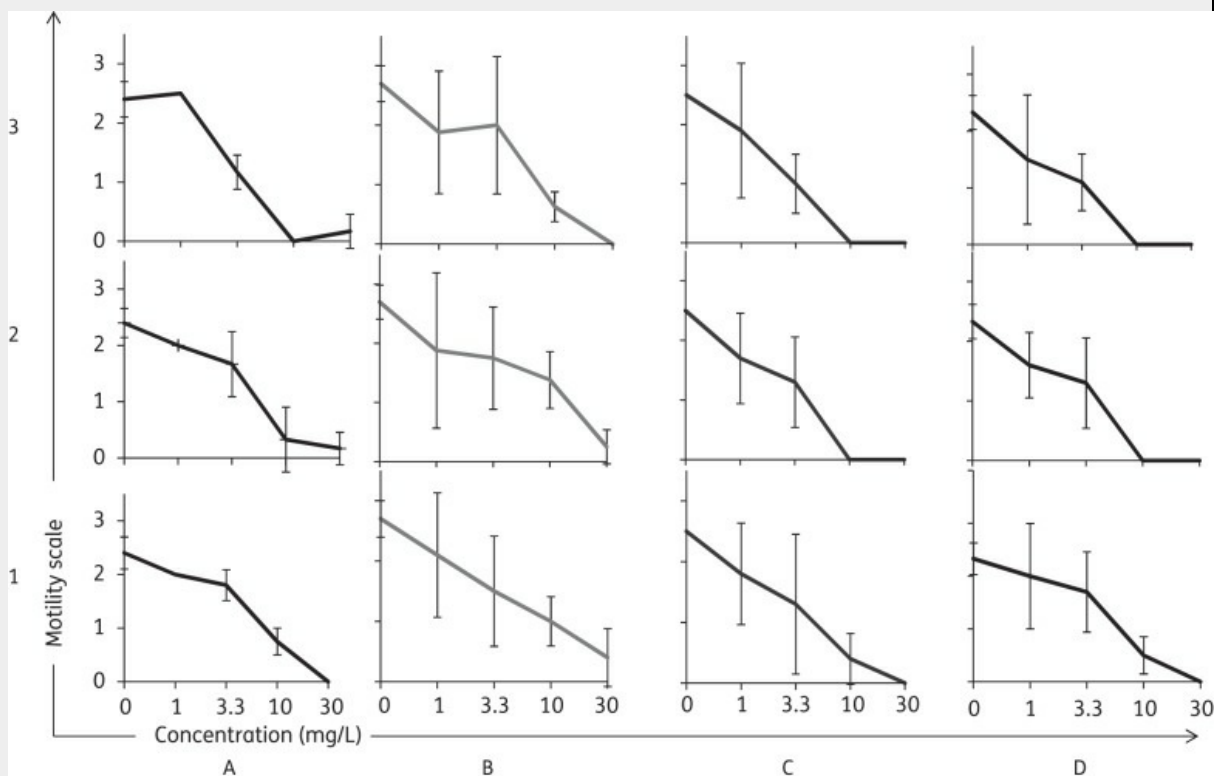


Figure 1.

Motility of adult schistosomes 72 h post-treatment with various concentrations (1.1, 3.3, 10 and 30 mg/L) of compounds 1, 2 or 3 in four different incubation settings. (a) Standard incubation with supplemented RPMI. (b) Addition of 2% red blood cells from red blood cell concentrate. (c) Addition of 120 μ M haemin. (d) Addition of 23 μ M haemoglobin.

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Table 2.

In vivo activity following a single oral dose of 400 mg/kg of selected 3-alkoxy-1,2-dioxolanes in mice harbouring juvenile or adult *S. mansoni*

Group	No. of mice investigated	No. of mice that died	No. of mice cured	TWR (%)	P value	FWBR (%)	P value
Control	8	0	0	—	—	—	—
Juvenile infection							
1	4	0	0	0	0.73	0	0.86
2	4	0	0	4.1	0.67	5.9	0.38
3	4	0	0	0	0.87	0	0.44
Adult infection							
1	4	0	0	42.5	0.27	47.1	0.23
2	4	0	0	37.0	0.35	41.2	0.35
3	4	0	0	15.1	0.86	17.7	0.73

TWR, total worm burden reduction; FWBR, female worm burden reduction.

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Table 3.

In vivo activity following a single oral dose of 400 mg/kg of selected 3-alkoxy-1,2-dioxolanes in mice harbouring adult *S. mansoni*

Group	No. of mice investigated	No. of mice that died	No. of mice cured	TWR (%)	P value	FWBR (%)	P value
Control ^a	7	0	0	—	—	—	—
Control ^b	9	0	0	—	—	—	—
15 ^a	4	1	0	32.0	0.1	37.8	0.1
16 ^a	4	1	0	12.0	0.7	5.4	0.7
17 ^a	4	1	0	21.3	0.4	35.1	0.3
18 ^b	4	0	0	16.4	0.9	11.9	0.7

TWR, total worm burden reduction; FWBR, female worm burden reduction.

^aVersus control.

^bVersus control.

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Table 4.

In vitro mortality of *E. caproni* worms at timepoints 24, 48 and 72 h post-drug treatment with selected compounds

Drug	Drug concentration (mg/L)	No. of worms observed	Percentage of worms that died after indicated time			
			0 h	24 h	48 h	72 h
Control	—	20	0	0	0	0
1	100	8	0	100		
	50	8	0	100		
	10	7	0	43	100	
	5	8	0	25	75	88
2	100	6	0	100		
	50	6	0	0	100	
	10	6	0	17	67	100
	5	7	0	0	29	57
3	100	6	0	100		
	50	7	0	100		
	10	7	0	57	100	

	5	9	0	22	100	
15	100	6	0	100		
	50	6	0	100		
	10	7	0	86	100	
	5	8	0	0	38	75
16	100	6	0	100		
	50	6	0	100		
	10	7	0	100		
	5	6	0	50	67	100
17	100	6	0	100		
	50	7	0	100		
	10	6	0	100		
	5	7	0	0	100	
18	100	6	0	100		
	50	7	0	100		
	10	6	0	67	83	100
	5	6	0	0	17	33

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Table 5.

In vivo activity following a single oral dose of 400 mg/kg of selected 3-alkoxy-1,2-dioxolanes against *E. caproni* in mice

Group	No. of mice investigated	No. of mice cured	Worms	TWR (%)	P value
Control	4	0	23.0 (0)	—	—
15	4	0	19.0 (7.2)	17.4	0.2
16	4	0	27.8 (4.5)	0	0.2
17	4	0	23.0 (7.8)	0	0.5

TWR, total worm burden reduction.

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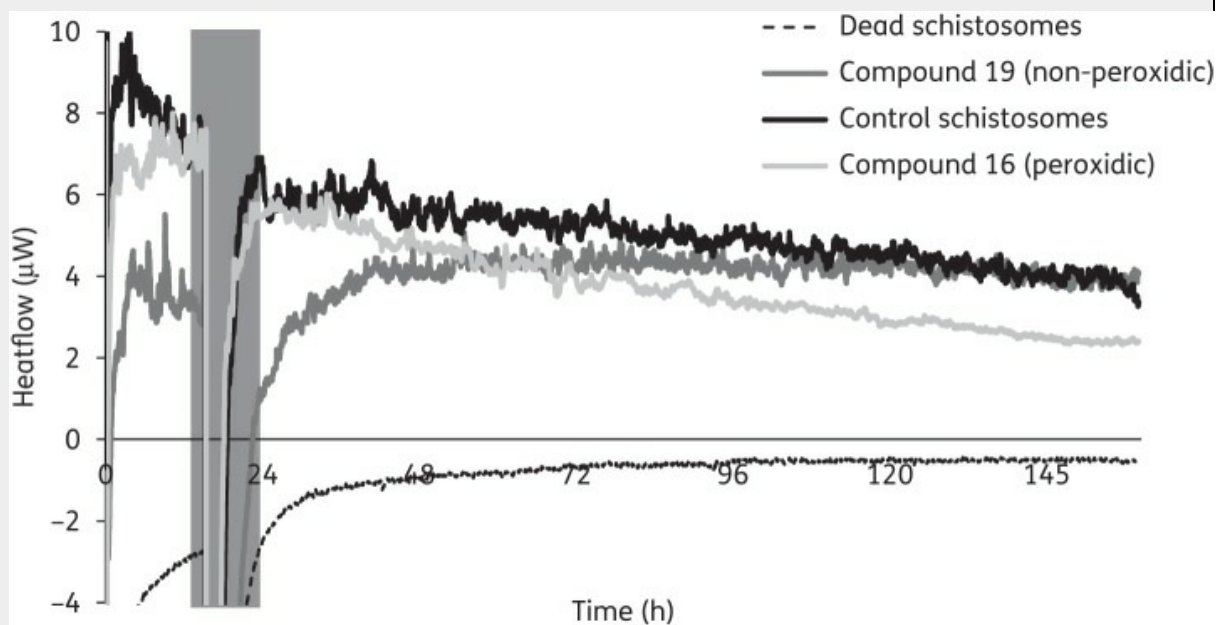


Figure 2.

Course of heat flow (μW) over time (h) after treatment of schistosomes with compound 19 (non-peroxidic) or compound 16 (peroxidic). Control schistosomes correspond to schistosomes treated with DMSO at the same concentration as used for drugs (0.3%). Amplitudes of curves represent the motility of schistosomes.

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