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Antihistomonal effects of artemisinin and *Artemisia annua* extracts *in vitro* could not be confirmed by *in vivo* experiments in turkeys and chickens

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Five different *Artemisia annua*-derived materials (i.e. dry leaves, pure artemisinin, and hexane, dichloromethane or methanol extracts of leaves) were screened for their *in vitro* activities against six clonal cultures of *Histomonas meleagridis*. Except for the methanol extract, all tested materials displayed *in vitro* activity against all tested protozoal clones. Neither the dry plant material, extracts nor artemisinin showed any antibacterial activity against the xenic bacteria accompanying the six *H. meleagridis* clones at concentration levels identical to the antihistomonal setting. The dichloromethane extract of dry leaves (Ext-DCM) (minimal lethal concentration = 1.0 mg/ml) and artemisinin (half-maximal inhibitory concentration = 1.295 mg/ml) had the most promising antihistomonal properties and were therefore subsequently tested in a standardized experimental infection model in both turkeys and chickens infected with clonal *H. meleagridis*. There were no differences between treatment groups, where all infected turkeys showed severe clinical histomonosis and demonstrated severe typhlohepatitis typical for histomonosis. Consistent with the infection model used, the infected chickens did not show any adverse clinical signs but contracted severe lesions in their caeca 7 and 10 days post infection (d.p.i.), liver lesions were absent to mild after 7 d.p.i. and progressed to severe lesions at 10 d.p.i.; thus no differences between treatment groups were observed. In conclusion, neither artemisinin nor Ext-DCM was able to prevent experimental histomonosis in turkeys and chickens at the given concentrations, which is contrary to the antihistomonal effect noticed *in vitro* even though the same clonal culture was used. The results of this study therefore clearly demonstrate the importance of defined *in vivo* experimentation in order to assess and verify *in vitro* results.

**Introduction**

Histomonosis is a parasitic disease in gallinaceous birds, primarily affecting turkeys and chickens. It causes severe lesions in the caecum and the liver and can lead to high mortality rates, especially in turkeys (McDougal, 2004). Infection with *Histomonas meleagridis* in poultry flocks has re-emerged since the ban of effective treatments (McDougal, 2005; Callait-Cardinal et al., 2007; Stokholm et al., 2010).

Previously used drugs have not yet been replaced resulting in an urgent need for new curative or prophylactic treatments. Several *in vitro* and *in vivo* experimental studies on chemotherapeutics have shown variable outcomes in finding a new and efficient therapy against *H. meleagridis* infections (Hu & McDougald, 2002; Hauck & Hafez, 2006; Bleyen et al., 2008; Hafez et al., 2010; Hauck et al., 2010b). Within recent years a trend towards non-chemotherapeutic alternative means has been set in the combat of histomonosis. Despite this awareness there is still only a limited number of *in vitro* studies on the effects of natural compounds on *H. meleagridis* available (Zennex et al., 2003; Grabensteiner et al., 2007, 2008; Hauck & Hafez, 2007; Arshad et al., 2008; van der Heijden & Landman, 2008a). The situation is similar when it comes to evaluating the impact of natural compounds on histomonosis *in vivo* (Duffy et al., 2004; 2005; Hafez & Hauck, 2006; Grabensteiner et al., 2008; van der Heijden & Landman, 2008b).

*Artemisia annua* has been used as an herbal infusion in traditional Chinese medicine for treatment of fevers, including malaria (Klayman, 1985). The sesquiterpene lactone artemisinin is one of the main active compounds of this medicinal plant and has been shown to be effective against various *Plasmodium* spp., including *Plasmodium falciiparum* that causes the most severe
form of malaria in humans (Qinghaosu Antimalaria Coordinating Research Group, 1979). Artemisinin-based combination therapies are presently recommended as first choice for uncomplicated antimalarial treatment by the World Health Organization (2010). Furthermore, several studies have shown promising effects of artemisinin against other pathogenic protozoa, including poultry coccidia (Allen et al., 1997, 1998; Brisibe et al., 2008; del Cacho et al., 2010). It has been demonstrated that supplementation of different levels of dried *A. annua* leaves in feed reduced the oocyst excretion in chickens experimentally infected with *Eimeria* spp. (Allen et al., 1997, 1998; Brisibe et al., 2008). Supplementing dried leaves or leaf extracts directly into poultry diets is an easy way to administer feed supplements in poultry flocks.

Since the discovery of artemisinin as an antimalarial drug several hypotheses on its mode of action have been suggested. The most plausible mode of action may be attributed to the cleavage of its endoperoxide bridge (Klayman, 1985; Olliaro et al., 2001). An iron-dependent mechanism leads to the cleavage of the endoperoxide bridge, producing free radicals that selectively target and inhibit the sarcoplasmic/endoplasmic reticulum Ca²⁺-ATPases pump (Eckstein-Ludwig et al., 2003). This mechanism has also been proposed in avian *Eimeria* spp., where inhibition of coccidian sarcoplasmic/endoplasmic reticulum Ca²⁺-ATPases was demonstrated recently (del Cacho et al., 2010). The molecular basis of metabolic processes in histomonads, such as if Ca²⁺ - dependent ATPases are present, has not yet been reported. In addition, it has been suggested that artemisinin disrupts the mitochondrial membrane in the malaria parasite (Li et al., 2001). Recently, it was demonstrated that artemisinin and its derivatives are distributed to malarial mitochondria, where they induce production of reactive oxygen species resulting in depolarization of the mitochondrial wall (Wang et al., 2010).

Therefore, one aim of the present study was to investigate whether a panel of extracts of *A. annua* leaves, as well as pure artemisinin, causes similar antiprotozoal effects on *H. meleagridis* in vitro. Significant inhibitory impact of the plant derivates on histomonads in *vitro* should be verified in *vivo* in a second step. Recently established in *vitro* propagated clonal cultures of *H. meleagridis* (Hess et al., 2006b) were used for screening the compounds in *vitro* (Grabensteiner et al., 2008) and to assess their effect in a standardized experimental infection model in both turkeys and chickens (Hess et al., 2006a).

**Materials and Methods**

**In vitro experiments.** *H. meleagridis* cultures. In the first experiment, six different clonal cultures of *H. meleagridis* (Table 1) were used to evaluate the effect of artemisinin and *A. annua* extracts. Clonal cultures were established through micromanipulation (Hess et al., 2006b). The screening was carried out on available low passage numbers of the clonal cultures, since it is well known that pathogenicity declines with increasing passages (Tyzzer, 1936; Hess et al., 2008). All experiments were performed in 2 ml Eppendorf tubes using protozoal cultures propagated for 48 h in Medium 199 supplemented with Earl’s salts, L-glutamine, 25 mM HEPES, L-amino acids (M199, Gibco®, Invitrogen®, Lofer, Austria), 2 mg/ml rice starch (Sigma-Aldrich, Vienna, Austria) and 15% foetal calf serum (Gibco®, Invitrogen®) at 40°C prior to testing. Cell suspensions of 10⁶ protozoa/ml were prepared by counting the number of viable cells in a Neubauer counting chamber.

**Table 1. Clonal *H. meleagridis* cultures used for screening of antiprotozoal properties of artemisinin and *A. annua* extracts.**

<table>
<thead>
<tr>
<th>Clonal culture</th>
<th>Abbreviation</th>
<th>Passage numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histomonas meleagridis/Chicken/</td>
<td>Hm2</td>
<td>45 to 47</td>
</tr>
<tr>
<td>Hungary/5009-C2/05</td>
<td>Hm3</td>
<td>21 to 23</td>
</tr>
<tr>
<td>Histomonas meleagridis/Turkey/</td>
<td>Hm4</td>
<td>38, 40 to 41</td>
</tr>
<tr>
<td>Austria/2877-C3/05</td>
<td>Hm6</td>
<td>24 to 26</td>
</tr>
<tr>
<td>Histomonas meleagridis/Turkey/</td>
<td>Hm7</td>
<td>19 to 21</td>
</tr>
<tr>
<td>Austria/8175-C7/06</td>
<td>Hm18</td>
<td>110 to 112</td>
</tr>
</tbody>
</table>

(Bright-Line® haemocytometer; Hauser Scientific, Horsham, Pennsylvania, USA, supplied by Sigma-Aldrich, Vienna, Austria) using Trypan blue (0.4%) (Gibco®, Invitrogen®, Lofer, Austria) to exclude non-viable cells. After centrifugation at 500 x g for 5 min, the protozoa were resuspended in M199 with 15% foetal calf serum without rice stach and the cell concentration was adjusted to 10⁶ protozoa/ml.

*A. annua* materials. Dry leaves from seed propagated *Artemisia annua* (cv. Artemis, F2 seeds, Mediplant, Conthey, Switzerland) cultivated at the Department of Food Science, Aarhus University, Årøskov, Denmark were finely ground before use. Artemisinin (purity > 99%) was obtained from Xiang Xi Holley Pharmaceutical Co., Ltd (Shanghai, China). Crude extracts from fresh thawed or dried *A. annua* leaves were made using hexane, dichlormethane or methanol. The crude extracts were filtered using a glass funnel and filter paper (AGF675, 400 mm, white ribbon filter, ashless, Frienetten, Knebel, Denmark) and evaporated at 30°C in vacuo using a rotary evaporator before the oily precipitate (extract) was used in further experiments.

Artemisinin and extracts were suspended (artemisinin, 1000 mg/ml) or dissolved (leaf extracts, 75 mg/ml) in dimethyl sulphoxide (DMSO) (purity 99.9%; Merck, Darmstadt, Germany). These were kept as stock solutions throughout the experiment. Dry leaf powder was put directly into 2 ml Eppendorf tubes and suspended in 100 µl M199 with 15% foetal calf serum prior to efficacy screening.

**Experimental set-up.** A test system previously described by Grabenstein et al. (2007) was used. For each tested clonal culture, positive and negative controls were included, consisting of 10⁶ protozoa/ml in fresh culture medium without the addition of *A. annua* materials (negative control) or with the addition of 0.4 mg/ml dimetridazole (positive control). The concentration levels of the materials in the test cultures were: dry leaf powder, 5, 10, 20, and 40 mg/ml; artemisinin, 5, 10, and 20 mg/ml; hexane extract (Ext-HEX), 500, 1000, and 1500 µg/ml; dichloromethane extract (Ext-DCM), 500, 1000, and 1500 µg/ml; and methanol extract (Ext-MeOH), 500, 1000, and 1500 µg/ml. Furthermore, hexane, dichloromethane and methanol were tested at 0.15% and DMSO at 2% added to aliquots consisting of 10⁶ protozoa/ml in fresh culture medium to assess the maximal effective dose of solvents in the test cultures.

Test cultures were put in 2 ml Eppendorf tubes and consisted of 100 µl compound solution (= stock solution diluted 1:10 with M199 with 15% foetal calf serum prior to inoculation), 800 µl culture medium consisting of M199, 2 mg/ml rice starch, and 15% foetal calf serum and 100 µl cell suspension with 10⁶ protozoa/ml, thus starting with 10⁷ protozoa/ml in all test cultures. Eppendorf tubes were incubated at 40°C for 48 h. Protozoal multiplication in all samples was evaluated 24 and 48 h after inoculation by counting the number of viable cells as described above. The mean of two counts was recorded for each replicate. Complete inhibition was confirmed by inoculation of 100 µl from the bottom of the respective cell suspension into 900 µl fresh medium without addition of any test material, where they were evaluated after 48 h of incubation at 40°C. The lowest concentration
for a given test material that led to complete inhibition in all clonal cultures with no live or motile protozoa after 24 h of incubation was determined as the minimal lethal concentration (MLC) (Grabensteiner et al., 2007).

In a second experiment, the effects of Ext-DCM from thawed fresh A. annua and dried leaves, respectively, against H. meleagridis/Turkey/Austria/2922-C6/04 were compared. The tested concentrations were 500, 1000, and 1500 µg/ml for both extracts. The experimental set-up and controls were as described above.

A third experiment was set up to determine the half-maximal inhibitory concentration (IC₅₀) of artemisinin, which is the concentration inhibiting 50% of the protozoal growth compared with the untreated control. In a similar set-up to the first experiment, protozoa from H. meleagridis/Turkey/Austria/2922-C6/04 were used to evaluate the inhibitory properties of artemisinin. Concentrations of artemisinin in the test solutions for determining the IC₅₀ were 10², 2 × 10², 4 × 10², 10³, 2 × 10³, 4 × 10³, 10⁴, 2 × 10⁴ and 4 × 10⁴ µM. The IC₅₀ was enumerated by graphical extrapolation using GraphPad Prism® 5 for Windows (GraphPad Software, San Diego, California, USA; www.graphpad.com).

**Antibacterial effect.** Bacteria present in the same monoeucaryotic Histomonas cultures as in the antiprotozoal setting were isolated using selective media—Columbia 5% sheep blood agar (aerobe, 37 °C for 24 h; Biorieux, Vienna, Austria), MacConkey agar (aerobe, 37 °C for 24 h; LAB M, Heywood, Lancashire, UK), Chromocult® Coliform Agar (aerobe, 37 °C for 24 h; Merck), Schaedler 5% sheep blood agar (anaerobe, 37 °C for 24 h; Biorieux), and Sabouraud Gentamycin Chloramphenicol agar (aerobe, 42 °C for 48 h; Biorieux)—and biochemical characterization methods—that is, catalase test (Bactident® Catalase; Merck) and Escherichia coli typing sera F1, F21, F103 for avian pathogenic E. coli (O1, O2, O78; Veterinary Laboratories Agency, New Haw, Addlestone, Surrey, UK).

The antibacterial activity was assessed using the disc diffusion method (Bauer et al., 1966; Clinical and Laboratory Standards Institute, 2008). Preparation of inoculum followed the Clinical and Laboratory Standards Institute Direct Colony Suspension Method (Clinical and Laboratory Standards Institute, 2008): therefore, colonies from agar plates grown for 24 h were suspended in PBS (Gibco®, Invitrogen®) and bacteria were evenly spread over the surface of the agar plates with sterile cotton swabs. Mueller Hinton plates (Biorieux) were used for E. coli and Proteus spp., whereas Columbia 5% sheep blood agar plates were used for Streptococcus spp. and Staphylococcus spp. Volumes of 20 µl of the test solutions in concentrations identical to those in the first experiment were loaded onto empty Sensi-discs (Oxoid Ltd, Cambridge, UK). Disks were loaded with 20 µl PBS as negative controls or with 10 µg meropenem (Oxoid Ltd) as positive controls.

**Statistical analysis.** All assays were performed in duplicate and repeated independently three times. The data analysis and statistical calculations were made using one-way analysis of variance followed by Tukey's multiple comparison test (GraphPad Prism® 5 for Windows; GraphPad Software, San Diego, California, USA; www.graphpad.com). P ≤ 0.05 was considered significant.

**In vitro experiments.** Based on the results from the in vitro experiments a bird experiment was set up in order to investigate the effect of artemisinin and Ext-DCM on a virulent clonal culture of H. meleagridis (H. meleagridis/Turkey/Austria/2922-C6/04) in turkeys and chickens (Table 2). Administration of artemisinin was done via feed and Ext-DCM via drinking water.

**Experimental birds and housing.** Sixty-five 1-day-old turkey poults (Big 6; Aviagen Turkeys Ltd, Tattenhall, UK) were randomly split into five groups with equal gender ratio (Groups I, II, III, IV and V) (Table 2). One hundred 1-day-old specific pathogen free chicks (VALO; Lohmann Tierzucht GmbH, Cuxhaven, Germany) were randomly split into four groups (Groups VI, VII, VIII and IX) (Table 2). On the first day of life all birds were individually marked using the Swiftag™ system (Heartland Animal Health Inc., Fair Play, Missouri, USA) before they were housed in pens on deep litter (wood shavings) in rooms under negative pressure. Birds without challenge infection were kept apart from the challenged birds in order to prevent contamination. Medicated or unmedicated water and feed were provided ad libitum.

All procedures performed on the birds were approved by the institutional ethics committee and licensed by the Austrian Government (licence number 68.205/0003-II/3b/2011).

**Feed and A. annua extracts.** Birds were supplemented with artemisinin in the feed or A. annua extract in the drinking water according to their groups (Table 2). Supplementation started at day 1 of life and was continued throughout the experimental period. The dosage was determined due to the obtained in vitro results and followed the protocol of Grabensteiner et al. (2008), in which in vivo dosages were calculated as two-fold of the MLC or IC₅₀.

All feed, medicated and unmedicated, used in the investigation were produced at the Department of Animal Science, Aarhus University, Viborg, Denmark. The nutritional composition of the base diets was adjusted according to the age of birds. Artemisinin (purity ≥ 99%; Trademax Pharmaceuticals & Chemicals Co., Ltd, Shanghai, China) was added to the diets in concentrations of 100 and 2600 mg/kg feed. Thus, both turkey and chicken feed were split into an unmedicated base diet, a diet supplemented with 100 mg/kg artemisinin and with 2600 mg/kg artemisinin.

Ext-DCM from dried A. annua leaves was dissolved in DMSO and administered as follows: from day 1 of life until day 15, the turkeys of Group I got drinking water supplied with 0.2% pure extract; from day 16 onwards the concentration was decreased to 0.1% due to reduced water intake. The chickens of Group VI were supplied with 0.1% extract in the drinking water from day 1 of life and onwards.

**Infection of the birds with a clonal culture of H. meleagridis.** At 14 days old, the birds were infected with H. meleagridis/Turkey/Austria/2922- C6/04 (Hess et al., 2006b) (in vitro passage 22). All turkey poults in Groups I, II, III and IV received 3 × 10⁸ H. meleagridis by the cloacal route using a conventional Eppendorf pipette. Birds of Group III died or had to be euthanized before inoculation was undertaken (see below). The chickens of Groups VI, VII and VIII were inoculated both orally and cloacally with 3 × 10⁸ H. meleagridis. For the oral inoculation, a crop tube placed on a syringe (1 ml Omniflux F solo; B. Braun

**Table 2. Overview of bird species, treatments and challenge infection with H. meleagridis/Turkey/Austria/2922-C6/04.**

<table>
<thead>
<tr>
<th>Group</th>
<th>Treatment</th>
<th>Number of birds</th>
<th>Challenge inoculum 300,000 H. meleagridis</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Ext-DCM 0.2% in drinking water (days 1 to 15); 0.1% (day 16 onwards)</td>
<td>15 turkeys</td>
<td>Cloacally</td>
</tr>
<tr>
<td>II</td>
<td>Artemisinin 100 mg/kg feed</td>
<td>15 turkeys</td>
<td>Cloacally</td>
</tr>
<tr>
<td>III</td>
<td>Artemisinin 2600 mg/kg feed</td>
<td>15 turkeys</td>
<td>Cloacally</td>
</tr>
<tr>
<td>IV, infection control</td>
<td>None</td>
<td>15 turkeys</td>
<td>Cloacally</td>
</tr>
<tr>
<td>V, negative control</td>
<td>None</td>
<td>5 turkeys</td>
<td>None</td>
</tr>
<tr>
<td>VI</td>
<td>Ext-DCM 0.1% in drinking water</td>
<td>30 chickens</td>
<td>Orally and cloacally</td>
</tr>
<tr>
<td>VII</td>
<td>Artemisinin 100 parts/10 in feed</td>
<td>30 chickens</td>
<td>Orally and cloacally</td>
</tr>
<tr>
<td>VIII</td>
<td>Infection control</td>
<td>None</td>
<td>30 chickens</td>
</tr>
<tr>
<td>IX, negative control</td>
<td>None</td>
<td>10 chickens</td>
<td>None</td>
</tr>
</tbody>
</table>
Melsungen AG, Melsungen, Germany) was used. The required numbers of H. meleagridis were adjusted into a volume of 300 μl Medium 199 + 15% foetal calf serum. Following inoculation, all birds were deprived from feed and water for 5 h.

Examination of the birds and sampling procedures. All birds were examined daily to detect any adverse clinical signs (e.g. diarrhoea, anorexia, behavioural changes) and mortality. Feed and water consumption were recorded daily. Body weight was measured weekly. Cloacal swabs were taken three times a week starting prior to infection in order to re-isolate and monitor the H. meleagridis excretion according to the protocol described recently (Hess et al., 2006a). All birds were sampled for blood once a week.

Euthanasia and post-mortem sampling. At 7 and 10 days post infection (d.p.i.), 15 chickens from each infected group (Groups VI, VII and VIII) and five chickens from the negative control (Group IX) were killed. Turkeys that survived the challenge were killed at termination of the experiment (d.p.i.), 15 chickens from each infected group (Groups VI, VII and VIII) and five chickens from the negative control (Group IX) were killed. Euthanasia due to severe histomonosis or killing of chickens at specific time points was performed by intravenous anaesthesia with thiopental followed by bleeding.

Pathological examination was performed on all birds. Lesions indicative for histomonosis in the caeca and the livers were noted with scores ranging from 0 for no lesions to 4 describing the most severe lesions, according to recently described protocols (Windisch & Hess, 2010; Zahoor et al., 2011).

Statistical analysis. Mortality data were analysed using the Gehan–Breslow–Wilcoxon test followed by the Bonferroni multiple comparison test, with a significance level P ≤ 0.05.

Results

In vitro experiments. Antiprotozoal effect. Antiprotozoal properties after 48 h of incubation are presented in detail in Table 3. For all treatments of the six clonal cultures, the number of viable protozoa is presented as the mean with standard deviations of the six replicates.

Addition of 5 mg dry leaf powder/ml did not result in significant reduction in any of the six clonal cultures (Hm2, Hm3, Hm4, Hm6, Hm7 and Hm18). In Hm3, Hm6, Hm7 and Hm18, protozoal growth was significantly lower at dry leaf powder levels of 10, 20 and 40 mg/ml. Hm2 showed a significant increase in protozoal growth when treated with 5 or 10 mg/ml dry leaf powder. Complete growth inhibition was seen at 20 and 40 mg/ml Hm2, Hm3, Hm6, Hm7 and Hm18, whereas complete inhibition of cell proliferation was only seen at 40 mg/ml dry leaf powder in Hm4. The MLC for dry leaf powder was determined to 40 mg/ml after 24 h.

For artemisinin, complete inhibition of protozoal proliferation was not observed in any of the six clonal cultures at 24 or 48 h following incubation with different concentrations (5, 10 and 20 mg/ml). However, significant reductions of histomonads were noticed after incubation for 48 h with artemisinin in the six cultures, ranging from 56.5 to 95.3% for 5 mg/ml, 70.3 to 96.9% in 10 mg/ml and 83.7 to 96.8% in 20 mg/ml compared with the untreated controls.

Growth of clonal cultures receiving 0.5 mg/ml Ext-HEX was significantly reduced in Hm2, Hm3 and Hm7, and the multiplication declined in all six clones at concentrations of 1.0 and 1.5 mg/ml Ext-HEX after 48 h. However, only 1.5 mg/ml resulted in complete inhibition in the six clonal cultures at 24 h of incubation. The MLC was determined to 1.5 mg/ml for Ext-HEX.

When adding Ext-DCM to the protozoa cultures, the three tested concentrations (0.5, 1.0 and 1.5 mg/ml) showed a significant inhibitory effect against histomonads of all clones. Complete inhibition of the cultures after 24 h of incubation was observed at Ext-DCM levels of 1.0 mg/ml and 1.5 mg/ml (MLC = 1.0 mg/ml).

In contrast to the other two extracts (Ext-HEX and Ext-DCM), Ext-MeOH was not able to induce complete inhibition in any of the tested clonal cultures of H. meleagridis. For Hm2, Hm3, Hm6 and Hm7 the growth after 48 h at the three concentration levels was not significantly different from the non-treated controls. Only Hm4 was significantly inhibited after 48 h at the three concentrations of 0.5, 1.0 and 1.5 mg/ml. A significant increase in number of viable histomonads was observed after addition of 0.5 mg/ml Ext-MeOH in cultures of Hm18.

Comparison of two sources of Ext-DCM. The tested concentrations of Ext-DCM extracted from dried A. annua leaves showed the same pattern in inhibition of H. meleagridis/Turkey/Austria/2922-C6/04 as Ext-DCM extracted from fresh leaves. Similar MLCs were confirmed in both extracts (1 mg/ml), thus justifying the use of dry leaf extracts in the in vivo study.

Determination of IC50 for artemisinin. The dose–response curve for artemisinin is shown in Figure 1, from which the IC50 for artemisinin after 48 h was determined by graphical interpolation to 4586 μM, which equals 1.295 mg/ml in test solution.

Antibacterial effect. In total, 19 bacterial strains were isolated. E. coli strains (8/19) were isolated at least once from all six H. meleagridis clonal cultures. E. coli serotypes O1, O2, or O78 were isolated from Hm3, Hm4, Hm6, and Hm7, Streptococcus spp. (5/19) were isolated from Hm3, Hm4, Hm6, and Hm7, Proteus spp. (5/19) were isolated from Hm2, Hm3, Hm4, and Hm18, and one Staphylococcus sp. was isolated from Hm18.

No inhibitory effect of dry leaf powder, artemisinin, Ext-HEX, Ext-DCM or Ext-MeOH was observed in any of the 19 isolated bacterial strains from the six investigated H. meleagridis clones.

In vivo experiments. Observations prior to challenge infection. The birds in Groups I, II, IV and V showed no decrease in activity, clinical signs or depression, whereas turkeys administered artemisinin 2600 mg/kg feed (Group III) started to show lower feed consumption. At days 5 to 7 following feeding, seven out of 15 birds from Group III died unexpectedly. At the same time, the remaining birds of Group III displayed increasing depression and anorexia and were therefore killed humanely on day 7. Post-mortem findings in Group III were: distended gallbladder (approximately 0.5 x 0.5 x 2 cm2; 15/15 birds), fatty-apparing pale liver (only present in killed birds; 8/15 birds), enlarged kidneys with increased tubular appearance (15/15 birds), urate deposits in ureters (15/15 birds), empty intestines (9/15 birds), soft long bones (9/15 birds) and beaks (6/15 birds).

Furthermore, it was observed that the water containing 0.2% Ext-DCM had a very pronounced strong herbal odour, which possibly decreased the intake of water of those turkeys (Group I) at 2 weeks of age to 60 to 70%
### Results of the in vitro activities of artemisinin, A. annua dry leaves and extracts against six clonal cultures of H. meleagridis after a 48-h incubation period expressed in number of protozoal cells

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Hm2</th>
<th>Hm3</th>
<th>Hm4</th>
<th>Hm6</th>
<th>Hm7</th>
<th>Hm18</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean and SD (10^4 protozoa)</td>
<td>Reduction (%)</td>
<td>Mean and SD (10^4 protozoa)</td>
<td>Reduction (%)</td>
<td>Mean and SD (10^4 protozoa)</td>
<td>Reduction (%)</td>
</tr>
<tr>
<td>Control</td>
<td>70 ± 12.1</td>
<td>45 ± 14.4</td>
<td>52 ± 8.5</td>
<td>39 ± 14.2</td>
<td>53 ± 8.0</td>
<td>80 ± 21.5</td>
</tr>
<tr>
<td>DMSO 2%</td>
<td>64 ± 21.1</td>
<td>25 ± 3.5a</td>
<td>43.7</td>
<td>29 ± 12.2</td>
<td>50 ± 9.3</td>
<td>100 ± 26.0</td>
</tr>
<tr>
<td>Dimetridazole 0.4 mg/ml</td>
<td>0 ± 0.0a</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Hexane 0.15%</td>
<td>73 ± 23.2</td>
<td>-4.5</td>
<td>39 ± 13.6</td>
<td>46 ± 13.3</td>
<td>50 ± 4.8</td>
<td>73 ± 10.9</td>
</tr>
<tr>
<td>Dichloromethane 0.15%</td>
<td>70 ± 19.7</td>
<td>-0.2</td>
<td>42 ± 18.8</td>
<td>40 ± 10.1</td>
<td>49 ± 2.7</td>
<td>66 ± 18.9</td>
</tr>
<tr>
<td>Methanol 0.15%</td>
<td>73 ± 19.9</td>
<td>-5.4</td>
<td>43 ± 11.3</td>
<td>41 ± 9.4</td>
<td>50 ± 9.6</td>
<td>86 ± 16.3</td>
</tr>
<tr>
<td>Dry plant 5 mg/ml</td>
<td>126 ± 27.4A</td>
<td>-80.9</td>
<td>63 ± 35.6</td>
<td>43 ± 45.5</td>
<td>63 ± 4.3</td>
<td>89 ± 23.9</td>
</tr>
<tr>
<td>Dry plant 10 mg/ml</td>
<td>100 ± 21.9a</td>
<td>-43.5</td>
<td>36 ± 25.5</td>
<td>9 ± 11.5</td>
<td>27 ± 11.7</td>
<td>48 ± 16.7</td>
</tr>
<tr>
<td>Dry plant 20 mg/ml</td>
<td>0 ± 0.0a</td>
<td>100.0</td>
<td>99.8</td>
<td>0 ± 0.0a</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Dry plant 40 mg/ml</td>
<td>0 ± 0.0a</td>
<td>100.0</td>
<td>100.0</td>
<td>0 ± 0.0a</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Artemisinin 5 mg/ml</td>
<td>11 ± 5.4A</td>
<td>83.7</td>
<td>5 ± 1.9</td>
<td>5 ± 3.0</td>
<td>23 ± 9.7</td>
<td>56.5</td>
</tr>
<tr>
<td>Artemisinin 10 mg/ml</td>
<td>8 ± 4.4A</td>
<td>88.1</td>
<td>3 ± 1.8</td>
<td>2 ± 1.0</td>
<td>16 ± 5.0</td>
<td>70.3</td>
</tr>
<tr>
<td>Artemisinin 20 mg/ml</td>
<td>4 ± 1.4A</td>
<td>94.7</td>
<td>2 ± 1.1</td>
<td>3 ± 2.3</td>
<td>96 ± 6.5</td>
<td>83.7</td>
</tr>
<tr>
<td>Ext-HEX 0.5 mg/ml</td>
<td>28 ± 7.8A</td>
<td>59.9</td>
<td>21 ± 6.1</td>
<td>38 ± 8.4</td>
<td>27 ± 9.7</td>
<td>63 ± 25.9</td>
</tr>
<tr>
<td>Ext-HEX 1.0 mg/ml</td>
<td>0 ± 0.0a</td>
<td>100.0</td>
<td>99.6</td>
<td>2 ± 4.2</td>
<td>95.6</td>
<td>100.0</td>
</tr>
<tr>
<td>Ext-HEX 1.5 mg/ml</td>
<td>0 ± 0.0a</td>
<td>100.0</td>
<td>100.0</td>
<td>0 ± 0.0a</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Ext-DCM 0.5 mg/ml</td>
<td>6 ± 6.3A</td>
<td>91.9</td>
<td>5 ± 4.6</td>
<td>5 ± 7.6</td>
<td>25 ± 8.0</td>
<td>53.2</td>
</tr>
<tr>
<td>Ext-DCM 1.0 mg/ml</td>
<td>0 ± 0.0a</td>
<td>100.0</td>
<td>100.0</td>
<td>0 ± 0.0a</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Ext-MeOH 0.5 mg/ml</td>
<td>88 ± 9.9</td>
<td>-26.6</td>
<td>53 ± 7.9</td>
<td>43 ± 6.3</td>
<td>54 ± 6.0</td>
<td>134 ± 22.9</td>
</tr>
<tr>
<td>Ext-MeOH 1.0 mg/ml</td>
<td>80 ± 10.0</td>
<td>-14.6</td>
<td>38 ± 7.0</td>
<td>20 ± 6.0</td>
<td>50 ± 10.1</td>
<td>107 ± 30.9</td>
</tr>
<tr>
<td>Ext-MeOH 1.5 mg/ml</td>
<td>71 ± 13.7</td>
<td>-1.6</td>
<td>22 ± 3.8</td>
<td>23 ± 9.3</td>
<td>48 ± 8.3</td>
<td>73 ± 18.5</td>
</tr>
</tbody>
</table>

aStatistical differences from clonal cultures without treatment are indicated with uppercase superscript letters (P ≤ 0.05). Data were analysed using one-way analysis of variance followed by Tukey’s multiple comparison test. SD, standard deviation.

bReduction of protozoan cells in comparison with the untreated clonal culture. “—” indicates an increase in growth compared with the untreated culture.
No live histomonads were recovered from turkeys or chickens prior to challenge infection. From infected turkeys the protozoa were re-isolated from cloacal swabs at 2 d.p.i. and onwards in all infected groups (Groups I, II and IV). In Groups I and IV, 100% of the birds excreted the parasite at least once during the experiment. Similarly, 14 out of 15 turkeys of Group II (application of 100 parts/10^6 artemisinin) had positive re-isolations. No histomonads could be recovered from any of the five turkeys in the negative control group (Group IX) at 3 days old showing neither significant pathological lesions nor signs of bacterial infection.

**Re-isolation of the parasite.** No live histomonads were recovered from turkeys or chickens prior to challenge infection. From infected turkeys the protozoa were re-isolated from cloacal swabs at 2 d.p.i. and onwards in all infected groups (Groups I, II and IV). In Groups I and IV, 100% of the birds excreted the parasite at least once during the experiment. Similarly, 14 out of 15 turkeys of Group II (application of 100 parts/10^6 artemisinin) had positive re-isolations. No histomonads could be recovered from any of the five turkeys in the negative control group (Group IX) throughout the experiment.

The excretion of histomonads from infected chickens was observed starting at 2 d.p.i. The number of chickens that were found positive by re-isolation at least once were: Group VI (0.1% Ext-DCM), 14/30 birds; Group VII (artemisinin 100 mg/kg feed), 12/30 birds; Group VIII (infected control group), 16/30 birds; and the negative control group (Group IX), 0/9 birds.

**Morbidity, mortality and pathological findings in infected turkeys.** All infected turkeys (Groups I, II and IV) showed various clinical signs of histomonosis, starting with general depression and ruffled feathers. Later on, sulphurous-coloured diarrhoea and sudden death became obvious in the afore-mentioned groups. Birds suffering from severe clinical signs were killed humanely.

The cumulative mortality of turkeys that died or were killed due to histomonosis is shown in Figure 2. Two birds from Group II (artemisinin 100 mg/kg feed) and one from the infection control (Group IV) overcame the challenge after 18 d.p.i. and were regarded as having survived the challenge. Consequently, the experiment was terminated at 20 d.p.i. by killing those three birds and all turkeys of Group V.

Turkeys that died due to histomonosis displayed severe disease-specific lesions in the caeca and livers. Furthermore, necropsy of the three surviving turkeys revealed severe lesions in the caeca and livers similar to pathological changes of turkeys that died from the disease. The lesions observed in the caeca and livers are shown in Table 4.

None of the chickens in any of the infected groups (Groups VI, VII and VIII) displayed clinical signs or died due to histomonosis. Nevertheless, necropsy of the chickens showed that the birds from the infected groups (Groups VI, VII and VIII) had severe lesions (lesion score = 3 to 4) in their caeca at 7 d.p.i. (see Table 4). On the same day, the majority of the infected chickens had no or mild gross lesions in the livers. Birds from the same groups displayed severe caecal lesions on day 10 after infection, which were accompanied by inflammation and necrosis of the livers. Organs of non-infected chickens of Group V were found normal during post-mortem examination.

**Discussion**

The present *in vitro* experiment revealed significant dose-dependent reductions in protozoal counts of all six tested clones of *H. meleagridis* for the tested concentrations of artemisinin and Ext-DCM.

In the first step, the direct effect of dried *A. annua* leaves against mono-eukaryotic *H. meleagridis* was investigated in an *in vitro* setting. Furthermore, it was...
aimed that in vitro investigations in this study could deliver necessary data for a pre-selection of the tested materials and concentrations that were most promising for further in vivo testing.

As shown in Table 3 there are remarkably varying properties, although dose dependent, both within a clonal culture and between clones. In all six clonal cultures a trend towards growth enhancement was seen when adding 5 mg/ml dry leaf powder. This was only significant in Hm2, however, where 5 mg/ml resulted in 80.9% increase in protozoa counts when compared with the control within this clone. The increase in the number of protozoa may partly be explained by the ability of the in vitro cultivated *H. meleagridis* to use different starch sources as demonstrated recently by Huack et al. (2010a), thus possibly also the starch fraction of *A. annua* (Brisibe et al., 2009). A dose of 40 mg/ml dry leaf powder was the only dosage that inhibited protozoal multiplication in all six clonal cultures, thus resulting in absolute death of the parasites after 24 and 48 h, respectively.

With regard to artemisinin, the parent compound isolated from *A. annua*, significant dose-dependent reductions in protozoal counts were observed for all six clones. Nevertheless, none of the concentrations was able to induce a total inhibition of histomonad proliferation. Hence, no MLC could be determined although reduction rates ranged from about 85 to 95% for Hm2, Hm3, Hm4, Hm6 and Hm18. Only a few in vitro studies have tested artemisinin and not its derivatives against protozoa, which were mainly intracellular parasites assessed in cell cultures—for example, *Toxoplasma gondii* (Nagamune et al., 2007; Hencken et al., 2010) or *Neospora caninum* (Kim et al., 2002). For evaluation of artemisinin IC50 values in vitro, two studies used procedures comparable with the present set-up against either *Trichomonas vaginalis* (Camuzat-Dedenis et al., 2001) or *Leishmania* spp. (Sen et al., 2010). Sen et al. (2010) obtained IC50 values on *Leishmania* spp. at artemisinin levels of 100 to 120 μM. This supports, as reviewed by White (2008) and Golenser et al. (2006), the in vitro activity of artemisinin on other protozoa being in the micromolar range. This concentration is considerably higher than the effective dose against the malaria parasite, which have IC50 values within the nanomolar range. In our first experiment, no MLC could be determined for artemisinin, and therefore the IC50 was determined based on the in vitro results to 4586 μM. This concentration is considerably higher than for malaria parasites. *H. meleagridis* is relatively different from obligate intracellular protozoa (e.g. *Plasmodium* spp.), for example by having resistant or cyst-like stages (Tyzzer, 1920; Zaragatzi et al., 2010) that may explain the higher IC50.

Ext-DCM was the most effective leaf extract, displaying complete inhibition of protozoal multiplication at 1.0 mg/ml in all clonal *H. meleagridis* cultures. This was superior to the Ext-MeOH, where no consistent inhibitory patterns were noticed between the six clonal cultures, and to some extent also the Ext-HEX, in which the MLC was determined to 1.5 mg/ml for the six tested *H. meleagridis* clones. This is in agreement with a recent study reporting that dichloromethane extracts from four different *Artemisia* spp. showed higher in vitro activity against bloodstream forms of *Trypanosoma brucei* than methanol extracts from the same plant species (Nibret & Wink, 2010). In addition to artemisinin and its derivatives, *A. annua* extracts contain a range of essential oil components (Nibret & Wink, 2010) and phenolic compounds (Ferreira et al., 2010). Camphor and 1,8-cineole were found to be the major components of *A. annua* L essential oil (Charles et al., 1991), which are capable of protecting chickens from pathological lesions after experimental infection with *Eimeria acervulina* or *Eimeria tenella* (Allen et al., 1997).

The comparison of Ext-DCM from dried *A. annua* leaves against Ext-DCM from fresh thawed *A. annua* leaves revealed identical MCLs, indicating similar in vitro antihistomonial properties. Therefore, further experiments were performed with the less laborious procedure using extracts of dry leaves.

At present histomonads need accompanying bacteria when cultured in vitro, but the role of the bacteria is not clear (McDougald, 2005). In order to assess whether the observed effects on *H. meleagridis* multiplication could be accounted as a direct or indirect effect, an antibacterial assay was performed on the accompanying xenic bacterial culture from all six clonal *H. meleagridis* cultures. No inhibitory effect on bacterial growth was noticed when treated with dried *A. annua* leaves, artemisinin or any of the three extract methods using compound concentrations as in the screenings for antihistomonial properties. It is known that artemether, a derivative of artemisinin, has no antibacterial effect on

### Table 4. Median hepatic and caecal lesion scores (LS) of turkeys suffering from histomonosis and of chickens at 7 and 10 d.p.i.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Turkeys</th>
<th>Chickens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mortality due to</td>
<td>Lesions specific to</td>
</tr>
<tr>
<td></td>
<td>histomonosis (number</td>
<td>histomonosis (number</td>
</tr>
<tr>
<td></td>
<td>of birds)</td>
<td>of birds)</td>
</tr>
<tr>
<td></td>
<td>Liver</td>
<td>Caecum</td>
</tr>
<tr>
<td>0.2% (0.1%) Ext-DCM</td>
<td>13/15</td>
<td>13/13</td>
</tr>
<tr>
<td>0.1% Ext-DCM</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Artemisinin</td>
<td>13/15</td>
<td>15/15</td>
</tr>
<tr>
<td>100 mg/kg feed</td>
<td>13/14</td>
<td>14/14</td>
</tr>
<tr>
<td>Infection control</td>
<td>0/5</td>
<td>0/5</td>
</tr>
<tr>
<td>Negative control</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

All birds were treated with artemisinin or *A. annua* leaf extract from first day of life and challenged at 2 weeks of age.

*Not applicable.*
human hospital strains of E. coli and Staphylococcus aureus (Esimore et al., 2002). Similar investigations found that artemisinin had no antibacterial effect on S. aureus (Dhingra et al., 2000; Slade et al., 2009). However, artemisinin showed antibacterial properties at 1 mg/ml against E. coli. E. coli NCTC 9002 and Proteus vulgaris (Dhingra et al., 2000). In our study, the amount of artemisinin loaded onto the discs ranged between 100 and 300 µg/disc (20 µl each test solution per disc), which had no antibacterial effect on the bacterial strains isolated from the clonal histomonal cultures. This is in agreement with a study where no antibacterial effect of 100 µg/disc artemisinin was found on E. coli or S. aureus (Shoeb et al., 1990). To the best of our knowledge, only a single study has addressed the antibacterial effect of essential oil components extracted from A. annua (Juteau et al., 2002). These authors demonstrated that the oily extract showed no inhibitory effect on E. coli and S. aureus, whereas complete inhibition was obtained for Enterococcus hirae at 0.1 mg/ml. A few other studies have been carried out on extracts of leaves from other related Artemisia species describing large variations on the inhibitory effect on E. coli, S. aureus and Proteus spp. (Rabe & van Staden, 1997; Ahameethunisa & Hopper, 2010; Seddik et al., 2010). The discrepancy between the efficacies of extracts may be explained by the different extraction methods, composition and purity of the tested extracts. Furthermore, extracts from different Artemisia species showing antibacterial effect were tested in concentrations several times higher than tested in the present work, in which a maximum of 10 to 30 µg extract per disc was used.

Combining the results of the antiprotozoal screening with the antibacterial tests, it is reasonable to assume that the observed inhibitory effect of dried A. annua leaves, artemisinin, Ext-HEX and Ext-DCM, is attributed to a direct effect on histomonads and could be regarded as antihistomonal. Ext-DCM and artemisinin were found to have the strongest antihistomonal effect in all tests and were therefore selected for further in vitro testing.

Turkeys received the challenge dose only cloacally as this is a proven route to establish infection in these birds (Liebhart et al., 2008). Data about the comparative oral or cloacal infection of chickens are not available, but it was shown that a combination of both routes of application with virulent histomonads caused severe lesions in the caeca and/or the liver (Zahoor et al., 2011). Therefore, chickens were infected via the crop and cloaca in order to ensure a successful infection.

Despite treatment with the test substances, the clinical outcome in turkeys was almost similar and of the same severity as noticed for the untreated but infected turkeys. Except three birds, all infected turkeys died or had to be killed due to severe clinical conditions.

Severe lesions in the caeca were present in all infected turkeys (median lesion score = 3 to 4) and chickens (median lesion score = 4), except for two turkeys (Group I) that were killed or died before the infection was established. Severe liver lesions were dominant in all infected turkeys regardless of treatment. In chickens, the liver affection progressed from very mild at 7 d.p.i. to severe at 10 d.p.i. independent of treatment. This indicates that neither artemisinin nor Ext-DCM had any protective effect on experimental histomonosis at the administered dose levels.

A possible explanation for the discrepancy between in vitro and in vivo efficacy of the present investigation is not obvious. It can be speculated that the low bioavailability (Titulaer et al., 1990) and the considerable self-induced hepatic first-pass metabolism of artemisinins seen in mammals (Gordi et al., 2005) may contribute insufficient concentrations of artemisinins in the birds. However, no information on the bioavailability and metabolism is yet available in poultry or avian species.

An explanation for the difference in efficacy between P. falciparum and H. meleagris could be that artemisinin and derivatives have a special affinity for malarial mitochondria (Wang et al., 2010) and H. meleagris does not possess mitochondria (Lindmark & Müller, 1973). In the in vitro experiments, the effective doses of artemisinin were in the micromolar range; therefore it can be suggested that the amount of artemisinin or the effective leaf extract fractions may have reached a level in which sufficient and lethal ratios of free radicals were obtained. Furthermore, no host interaction or metabolism was disturbing the direct effect on H. meleagris when treated in vitro.

The post-mortem findings from the turkey group administered artemisinin 2600 mg/kg feed (Group III) may be indicative of intoxication, and further investigations are ongoing and will be discussed elsewhere. Although very little information on the toxicological profile of A. annua plant material and extracts, including artemisinin, in poultry is available, it has recently been investigated in broiler chickens (Arab et al., 2009; Shahbazfar et al., 2011). Hepatic and renal degeneration was seen histopathologically regardless of dose (17 to 136 mg/kg feed) after long-term oral administration of artemisinin, whereas neuronal degeneration seemed to be dose dependent, even though no clinical signs were present (Shahbazfar et al., 2011). Furthermore, single doses of 1250 mg/kg and 2500 mg/kg showed similar patterns in clinical and histopathological findings, as well as bile retention in the liver (Arab et al., 2009).

In conclusion, dry leaves and three extracts from A. annua as well as the main antimalarial constituent of this plant, artemisinin, were evaluated for the first time for their antihistomonal activities in vitro against six different clonal cultures of H. meleagris. Four of the tested materials displayed in vitro activity against all protozoal clones. However, neither artemisinin nor Ext-DCM that were tested in vivo was able to prevent experimental histomonosis in turkeys or chickens at the given concentrations, although the clonal culture used for this investigation was one of the in vitro tested clones. Thus, the results of this study clearly demonstrate the importance of defined in vivo experiments in order to assess and verify in vitro results.

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