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1 **An example of molecular co-evolution: reactive oxygen species (ROS) and ROS scavenger**  
2 **levels in *Schistosoma mansoni*/*Biomphalaria glabrata* interactions**

3

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23 **Abstract**

24           The co-evolution between hosts and parasites involves huge reciprocal selective pressures  
25 on both protagonists. However, relatively few reports have evaluated the impact of these reciprocal  
26 pressures on the molecular determinants at the core of the relevant interaction, such as the factors  
27 influencing parasitic virulence and host resistance. Here, we address this question in a host-parasite  
28 model that allows co-evolution to be monitored in the field: the interaction between the mollusk,  
29 *Biomphalaria glabrata*, and its trematode parasite, *Schistosoma mansoni*. Reactive oxygen species  
30 (ROS) produced by the hemocytes of *B. glabrata* are known to play a crucial role in killing *S.*  
31 *mansoni*. Therefore, the parasite must defend itself against oxidative damage caused by ROS using  
32 ROS scavengers in order to survive. In this context, ROS and ROS scavengers are involved in a co-  
33 evolutionary arms race, and their respective production levels by sympatric host and parasite could  
34 be expected to be closely related. Here, we test this hypothesis by comparing host oxidant and  
35 parasite antioxidant capabilities between two *S. mansoni/B. glabrata* populations that have co-  
36 evolved independently. As expected, our findings show a clear link between the oxidant and  
37 antioxidant levels, presumably resulting from sympatric co-evolution. We believe this work  
38 provides the first supporting evidence of the Red Queen Hypothesis of reciprocal evolution for  
39 functional traits at the field-level in a model involving a host and a eukaryotic parasite.

40

41 *Keywords:* Host-parasite co-evolution, *Schistosoma mansoni*, *Biomphalaria glabrata*, Reactive  
42 oxygen species (ROS), ROS scavengers

43

## 44 **1. Introduction**

45           Understanding the co-evolution of host-parasite interactions represents a challenge in  
46 evolutionary biology. Parasites cause substantial deleterious effects on their hosts, and therefore  
47 represent a major driving force in their evolution (Howard, 1991). Similarly, the host immune  
48 defenses represent the major selective pressure driving the evolution of parasites. For parasites to  
49 survive and develop in the host they must adapt to the host-defense system or they will die. This  
50 parallel co-evolution of host-parasite interactions can be viewed as an arms race in which both the  
51 host and the parasite develop mechanisms to circumvent the weapons developed by their opponent.  
52 In this context of reciprocal co-evolution, illustrated by Van Valen (1974), under the Red Queen  
53 Hypothesis it is assumed that the parasitic genes responsible for infectivity will evolve alongside the  
54 host defense genes, resulting in adaptation of the interactions between local host and parasite  
55 populations (Dybdahl and Storfer, 2003). To date, however, only a few studies have sought to  
56 verify this prediction and convincing experiments have only been reported for models involving  
57 viruses, bacteria and unicellular eukaryotes (Lohse et al., 2006; Forde et al., 2008).

58           Demonstrating co-evolution in an animal host-parasite system is not straightforward and  
59 most prior discussions of such processes have been indirect, as in studies describing local  
60 adaptation when compatibility is higher between sympatric host-parasite combinations than  
61 between allopatric combinations (Gasnier et al., 2000; Gagneux et al., 2006; Munoz-Antoli et al.),  
62 or studies that have focused on only one trait of the interaction, such as host resistance (Green et al.,  
63 2000) or parasite infectivity (Little et al., 2006). Moreover it is important to take into account that  
64 non-co-evolutionary mechanisms could also explain correlations between the traits of interacting  
65 species and that the absence of correlated traits is not evidence for an absence of co-evolution  
66 (Nuismer et al., 2007, 2010; Yoder and Nuismer, 2010). However we assume that the direct  
67 examination of reciprocal selection in both the host and the parasite could provide supporting  
68 evidence of co-evolution.

69 Two relatively recent studies investigated this reciprocal response more thoroughly. In the  
70 first, reciprocal changes in resistance and infectivity were identified for co-evolving *Potamopyrgus*  
71 snail hosts and their trematode parasites; however, while these changes were identified using  
72 prevalence phenotypes, they were not supported by the studied functional markers (Koskella and  
73 Lively, 2007). The second report provided experimental support for the reciprocity of adaptation  
74 costs, rapid genetic changes and increased genetic diversity during the co-evolution of a  
75 multicellular host, the nematode *Caenorhabditis elegans*, and its pathogenic bacteria, the Gram-  
76 positive bacterium, *Bacillus thuringiensis* (Schulte et al., 2010). In both papers, co-evolution was  
77 studied using laboratory strains selected by experimental evolutionary approaches, and only the  
78 second paper focused on molecular changes induced by the co-evolutionary process. Both papers  
79 were based on an "over time" approach in which the evolution of phenotypes was monitored over  
80 the course of experimental laboratory generations. Other empirical studies have been based on a  
81 "point time" approach in which the pattern of co-variations between host-parasite populations or  
82 strains that co-evolved independently were assessed at a single experimental time point (Forde et  
83 al., 2004; Morgan et al., 2005).

84 Here, we investigated the reciprocal evolution of molecular mechanisms directly at the core  
85 of the host-parasite interaction in a natural system of co-evolution, by comparing host and parasite  
86 populations that have co-evolved independently. As a model, we used the interaction between the  
87 trematode, *Schistosoma mansoni* (responsible for human intestinal schistosomiasis), and its mollusk  
88 intermediate host, *Biomphalaria glabrata*. This interaction is a model of choice for the study of  
89 potential co-evolutionary dynamics (Webster and Davies, 2001; Webster et al., 2004; Beltran and  
90 Boissier, 2008; Beltran et al., 2008; Bouchut et al., 2008; Roger et al., 2008a; Roger et al., 2008b;  
91 Roger et al., 2008c; Steinauer, 2009).

92 During its intramolluskal stage, the parasite must cope with the snail's immune system. One  
93 of the main immune effectors in mollusks are the reactive oxygen species (ROS) produced by  
94 hemocytes (the circulating immune cells of snails) (Hahn et al., 2000; de Jong-Brink et al., 2001;

95 Hahn et al., 2001b; Mourao et al., 2009b). Previous studies conducted by Hahn and co-workers  
96 demonstrated that hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) plays a crucial role in the killing of *S. mansoni*  
97 sporocysts (Hahn et al., 2001a, b). Furthermore, hemocytes from *S. mansoni*-resistant snails were  
98 shown to generate significantly more H<sub>2</sub>O<sub>2</sub> than susceptible snails, perhaps due at least in part to the  
99 former having constitutively elevated levels of the mRNA encoding the copper/zinc superoxide  
100 dismutase (Cu-ZN SOD) (Goodall et al., 2004; Bender et al., 2005; Bender et al., 2007). To resist  
101 ROS-mediated attacks, the *S. mansoni* larvae produce ROS-detoxifying enzymes (Vermeire et al.,  
102 2006; Guillou et al., 2007; Vermeire and Yoshino, 2007; Roger et al., 2008c; Wu et al., 2009),  
103 several of which appear to be secreted by sporocysts (Guillou et al., 2007; Wu et al., 2009).  
104 Supporting this, a recent report showed that antioxidant enzymes produced by *S. mansoni*  
105 sporocysts are directly involved in protecting the pathogen against immune cell-mediated oxidative  
106 stress (Mourao et al., 2009b).

107 In this context, the snail-produced ROS and the parasite-produced ROS scavengers are  
108 involved in a co-evolutionary arms race, and we can hypothesize that their production levels will be  
109 closely related. Here, we tested this hypothesis by comparing host oxidant and parasite antioxidant  
110 abilities for two *S. mansoni*/*B. glabrata* strains that have evolved independently, originated from  
111 different geographic endemic zones and which are found to display significant differences in  
112 compatibility.

113

## 114 **2. Materials and methods**

### 115 *2.1 Ethics statement*

116 Our laboratory has received the permit # A66040 for experiments on animals from both the French  
117 Ministry of agriculture and Fishing and the French Ministry of National Education, Research and  
118 Technology. Housing, breeding and animal care of the mice followed the ethical requirements of  
119 French government. The experimenter possesses the official certificate for animal experimentation

120 delivered by both ministries (Décret # 87–848 du 19 octobre 1987; number of the authorization  
121 007083).

122

## 123 2.2. *Biological materials*

124 Two strains of *S. mansoni* were used in this study: a Brazilian strain (*SmBRE*) and a  
125 Guadeloupean strain (*SmGH2*). Each strain was maintained: (i) in their sympatric strain of *B.*  
126 *glabrata* (*BgBRE* and *BgGUA*, respectively); and (ii) in hamsters (*Mesocricetus auratus*), as  
127 described previously (Théron et al., 1997).

128 Miracidia from *SmBRE* and *SmGH2* were hatched from eggs axenically recovered from 60-  
129 day-infected hamster livers, according to the previously described procedure (Roger et al., 2008c).  
130 Briefly, livers were collected and kept overnight at 4°C in sterile saline solution (NaCl 150 mM)  
131 containing an antibiotic/antimycotic mixture (penicillin 100 units/ml, streptomycin 0.1 mg/ml,  
132 amphotericin B 0.25 µg/ml; Sigma). The livers were then homogenized and the eggs were filtered  
133 out, washed, and transferred to spring water. The miracidia were allowed to hatch out under  
134 illumination.

135

## 136 2.3. *Schistosome-snail compatibility: snail exposure, infection rates and intensities*

137 The compatibilities of the tested snail-schistosome combinations were evaluated by  
138 monitoring the infection rates (% of snails infected) and the intensity of infection (number of  
139 mother sporocysts (SpI) developed) among snails individually challenged with different numbers of  
140 miracidia. As the miracidial dose increased, a larger fraction of the phenotypic diversity in the  
141 parasitic isolate was sampled; thus, dose-response curves are much more informative than single-  
142 dose challenges when examining the dynamics of compatibility between two host-parasite  
143 combinations (Théron et al., 2008).

144 For each experiment, snails (7-9 mm in diameter) were exposed individually to a fixed  
145 number of miracidia in approximately 10 ml of water for 8 h. Following exposure to miracidia, the

146 snails were replaced in their original containers until their infection status (presence of SpI) was  
147 assessed. For the detection of SpI, the snails were fixed 15 days post-exposure, following  
148 previously described methods (Gerard et al., 1995; Moné et al., 2010b). In brief, each snail was  
149 relaxed in pond water containing an excess of crystalline menthol for 6 h, the body was removed  
150 and fixed in modified Raillet-Henry's solution, exhaustive dissection of the head-foot zone was  
151 performed, and the number of SpI present in each snail (readily observable as translucent white  
152 bodies within an opaque gray tissue background) was determined.

153 Dose-response curves were obtained by challenging individual snails (30-40 snails per  
154 treatment) with doses of 1, 10, 20, 30 and 50 miracidia. Compatibility was measured for the two  
155 sympatric combinations (*SmBRE* versus *BgBRE* and *SmGH2* versus *BgGUA*) and the two  
156 allopatric combinations (*SmBRE* versus *BgGUA* and *SmGH2* versus *BgBRE*).

157

#### 158 2.4. Cytotoxicity of $H_2O_2$ on *S. mansoni* sporocysts

159  $H_2O_2$  cytotoxicity was measured using the Roche Cytotoxicity Detection Kit (Roche  
160 Diagnostics, Mannheim, Germany), which is based on the measurement of lactate dehydrogenase  
161 (LDH) activity released from dead and lysed cells into the supernatant. Four hundred miracidia each  
162 of *SmBRE* and *SmGH2* were submitted to in vitro transformation to obtain primary sporocysts  
163 (Sp1). Briefly, the miracidia were cultured for 24 h in sterile Chernin's balanced salt solution  
164 (CBSS) (Chernin, 1963), containing an antibiotic/antimycotic mixture (penicillin 100 units/ml,  
165 streptomycin 0.1 mg/ml, amphotericin B 0.25  $\mu$ g/ml; Sigma). The sporocysts were then exposed to  
166 four different concentrations of  $H_2O_2$  (0, 75, 150 and 200  $\mu$ M) for 2 h and cytotoxicity was  
167 examined according to the manufacturer's instructions. As a positive control, we measured LDH  
168 release from Sp1 that had been lysed with the provided lysis solution (high control, HC); this was  
169 taken as 100% LDH release. To correct for the background, we measured LDH levels in Sp1-free  
170  $H_2O_2$ -treated culture medium (substance control, SC). All measured values were assayed in



171 triplicate. The percentage of specific H<sub>2</sub>O<sub>2</sub>-induced LDH release was determined as: % cytotoxicity  
172 = [(experimental result - SC)/(HC - SC)] x 100.

173

#### 174 2.5. Effect of H<sub>2</sub>O<sub>2</sub> on *S. mansoni* sporocyst mortality

175 Two independent experiments were conducted in triplicate on 24-well plates containing 20  
176 Sp1 (representing *SmBRE* or *SmGH2*) per well. The Sp1 were in-vitro transformed as described  
177 above (see Materials and methods section 2.2), and exposed to 0, 200, 400, 800 or 1,600 µM of  
178 H<sub>2</sub>O<sub>2</sub> (Hydrogen peroxide 35%, FLUKA, Germany) for 4 h. Mortality was assessed under a light  
179 microscope, with the Sp1 considered “dead” when we failed to observe motility and/or the beating  
180 of the flame-cell flagella.

181

#### 182 2.6. The total antioxidant capacity of *S. mansoni* sporocysts

183 The cumulative (total) antioxidant capacity of the sporocysts was quantified for the two  
184 parasite strains, *SmBRE* and *SmGH2*, using an Antioxidant Assay Kit (Sigma). For each test, 2,000  
185 sporocysts were in-vitro transformed as described above. After 24 h, fully transformed sporocysts  
186 were recovered by gentle centrifugation (800 g, 5 min, 4°C). The samples were then disrupted by  
187 sonication (three pulses of 20 s each) and pelleted by centrifugation (12,000 g, 15 min, 4°C), and  
188 the antioxidant capacity of each supernatant was determined following the manufacturer’s  
189 recommendations. The amount of protein in each supernatant was determined using a Bradford  
190 protein assay kit and used as a correcting factor. The experiment was performed six times per strain.

191

#### 192 2.7. Reverse Transcription-quantitative PCR (RT-qPCR)

193 *RT-qPCR* analyses were conducted to compare the expression of parasite antioxidant  
194 enzymes suspected to play key roles in the detoxification of host-induced oxidative stress. Real-  
195 time PCR analyses were performed using a LightCycler 2.0 system (Roche Applied Science) and a  
196 LightCycler Faststart DNA Master SYBR Green I kit (Roche Applied Science). Total RNA  
197 extractions from miracidia were performed using the Trizol Reagent (Life Technologies, USA) and

198 the manufacturer's protocol. Reverse transcription was performed according to previously described  
199 procedures (Guillou et al., 2004). qPCR amplification was performed using 2.5 µl of cDNA in a  
200 final volume of 10 µl containing 3 mM MgCl<sub>2</sub>, 0.5 µM of each primer and 1 µl of master mix. The  
201 primers were designed using either the LightCycler probe design software or the web-based  
202 Primer3 plus interface (<http://www.bioinformatics.nl/cgi-bin/primer3plus/primer3plus.cgi>) and are  
203 given in Table 1. The following Light-Cycler run protocol was used: denaturation at 95°C for 10  
204 min, followed by 40 cycles of amplification and quantification at 95°C for 10 s, 60°C for 5 s and  
205 72°C for 16 s, a melting curve of 60–95°C with a heating rate of 0.1°C/s and continuous  
206 fluorescence measurement, and then a cooling step to 40°C. For each reaction, the cycle threshold  
207 (Ct) was determined using the “Fit Point Method” of the LightCycler Software, version 3.3. The  
208 PCR reactions were performed in duplicate and the mean Ct value was calculated. For each sample,  
209 the expression level of the target gene was normalized with regard to the expression of two  
210 constitutively expressed genes (28S rRNA and α tubulin). The expression ratio (R) was calculated  
211 according to the formula:  $R = 2^{(\Delta Ct)}$ , where  $\Delta Ct$  represents Ct (target gene) – Ct (constitutively  
212 expressed gene).

213

#### 214 *2.8. ROS detection in single cells*

215 The cell-permeable fluorescent oxygen probe, 1-pyrenebutyric acid (PBA), can be used for  
216 the measurement of free radicals in solution (Oter and Ribou, 2009) and in living cells (Ribou et al.,  
217 2004; Rharass et al., 2006), with the fluorescence intensity and lifetime of PBA decreasing  
218 proportionately to the free-radical concentration. Measurement of the fluorescent lifetime offers  
219 many advantages over intensity based measurements when working in vivo, not the least that the  
220 measurements are independent of the absolute intensity of emitted light and the fluorophore  
221 concentration, thereby avoiding artifacts arising from optical losses. Moreover, these probes do not  
222 require a reaction with ROS, are usually stable and the fluorescent lifetime is not modified by probe  
223 degradation or variations in its intracellular accumulation.

224

225 *2.8.1. Staining and fixation*

226 Hemolymph samples were recovered from *BgBRE* and *BgGUA* snails, and aliquots (150  $\mu$ l)  
227 were put in a Sykes-Moore chamber. After 4 h, the adhered hemocytes were rinsed with Hank's  
228 buffered salt solution (HBSS) and stained for 20 min with PBA (Acros Organics, Belgium; 0.10  
229  $\mu$ M in 1% ethanol). The hemocytes were then rinsed three times and placed in HBSS for  
230 measurements. For fixation experiments, hemocytes were treated as described above except that  
231 after the final rinsing step, the cells were killed by incubation for 10 min in Baker solution (10%  
232 paraformaldehyde in 1% aqueous calcium chloride). In the latter case, the experiments were  
233 performed within 1 h after cell killing, in order to avoid probe reorganization (Ribou et al., 2004).

234

235 *2.8.2. ROS quantification by fluorescent-lifetime measurement of single cells*

236 The fluorescent decay of single living cells loaded with PBA was recorded using time-  
237 resolved microfluorimetry, as previously described (Ribou et al., 2003). Briefly, a laser (nitrogen  
238 laser NL100; Stanford Research Systems, USA) delivered monochromatic 337-nm pulses, each  
239 with a half-amplitude pulse-width of 3 ns, and an objective (40 $\times$ ; Unitron) was used to concentrate  
240 the excitation beam on the microscopic sample. Emitted photons were collected and focused on a  
241 photomultiplier 1P28 (Hamamatsu Corporation, Japan). A diaphragm placed on the emission  
242 pathway allowed the selection of signals from single cells, while a 404-nm bandpass filter (half  
243 bandwidth; 40 nm) also located along the emission pathway was used to select the pyrene emission.  
244 Each signal was digitalized by a digital oscilloscope (TDS 3032C; Tektronix, USA). The  
245 fluorescent decay of single PBA-loaded cells selected by the 404-nm filter could be resolved into  
246 three exponential curves. The time constants (i.e. lifetimes) and amplitude values of each  
247 exponential curve in the decay were obtained using the downhill simplex method (Nelder and  
248 Mead, 1965). The first two decays corresponded to the intrinsic fluorescence of the cell attributed to  
249 the reduced form of NAD(P)H. The third long-time constant ( $> 100$  ns), which was characteristic of

250 pyrene derivatives, was related to the ROS concentration through the Stern-Volmer equation (Stern  
251 and Volmer, 1919) that describes collisional fluorescent quenching of a probe (i.e. PBA) by a  
252 quencher (i.e., free radicals). The method has been described in several papers (Ribou et al., 2003;  
253 Ribou et al., 2004; Rharass et al., 2006). We calculated the variation of intracellular ROS  
254 concentrations as follows:

$$255 \quad [ROS] / [ROS]_m = [t_m (t_0 - t)] / [t(t_0 - t_m)] \quad \text{Equation 1}$$

256 where  $t$  is the fluorescent lifetime measured for 108 single hemocytes originating from eight  
257 *BgBRE* snails and 111 cells from eight *BgGUA* snails;  $t_m$  is the mean of all lifetimes; and  $t_0$  is the  
258 fluorescent lifetime in the absence of ROS (measured from dead hemocytes fixed with Baker  
259 solution). In this equation,  $[ROS]_m$  is the mean of the concentrations from all tested cells (219  
260 cells). We assumed that fixation ended all cellular activity and ROS production. In the presented  
261 data, the mean ROS concentration has been assigned an arbitrary value of 1.

262

### 263 2.9. $H_2O_2$ production and release by *B. glabrata* hemocytes

264 The  $H_2O_2$  production by hemocytes was measured using Amplex® Red (Invitrogen).  
265 Hemolymph was collected from the head-foot regions of *BgBRE* and *BgGUA* snails (7-11 mm in  
266 diameter) as previously described (Bouchut et al., 2006), and the number of hemocytes per  $\mu$ l of  
267 hemolymph was quantified using a cell counter (Z Series Coulter Counter; Beckman Coulter);  
268  $226.2 \pm 50.6$  cells / $\mu$ l and  $241.2 \pm 102.1$  cells / $\mu$ l were obtained for *BgBRE* and *BgGUA*,  
269 respectively. The Hemolymph of four snails was pooled and 45,000 hemocytes per well were  
270 dispensed to a 96-well plate for each strain. The hemocytes were allowed to adhere and spread for 1  
271 h at 26°C. The plate was then centrifuged (600g for 10 min), the plasma was removed, the adhered  
272 hemocytes were washed three times with HBSS, and the wells were treated with Amplex® Red  
273 reaction mixture (100  $\mu$ L per well, prepared according to the manufacturer's instructions). Optical  
274 density was measured with a microplate reader at 570 nm during the following 1 h (at 5, 10, 15, 20,  
275 30, 40, 50, 60 min). The results are expressed as Amplex Red O.D. at 570 nm / 45,000 cells.

276

277 *2.10. Biomphalaria glabrata superoxide anion plasma content*

278 The plasma content of superoxide anion was monitored via the superoxide-mediated  
279 reduction of nitroblue tetrazolium (NBT), which results in the precipitation of an insoluble blue  
280 formazan that can be quantified spectrophotometrically. Briefly, hemolymph was collected from  
281 *BgBRE* and *BgGUA* snails as described above. Hemocytes were removed by centrifugation (1,500  
282 g for 15 min), and then 50  $\mu$ L of plasma from each snail was mixed with 50  $\mu$ l of 0.1% NBT  
283 (Sigma) dissolved in PBS; ( $\text{Na}_2\text{HPO}_4$  8.41 mM,  $\text{NaH}_2\text{PO}_4$  1.65 mM, NaCl 45.34 mM, pH 7.45).  
284 Formazan blue formation was measured with a microplate reader at 620 nm over the course of 3 h  
285 (at 5, 10, 15, 30, 60, 90, 180 min). NBT-free plasma was used as a control, and triplicate  
286 experiments were conducted for 10 individuals per strain.

287

288 *2.11. Statistical analyses*

289 The normality of our experimental data was assessed using the Shapiro-Wilk normality test  
290 (Shapiro and Wilk, 1965). Our data on the effect of  $\text{H}_2\text{O}_2$  cytotoxicity on *S. mansoni* sporocysts  
291 (LDH test), *B. glabrata* hemocyte  $\text{H}_2\text{O}_2$  production, and superoxide anion plasma content were all  
292 found to be normally distributed ( $P > 0.05$ ), and were subsequently analyzed using the student's *t*-  
293 test. Our data on the effect of  $\text{H}_2\text{O}_2$  on *S. mansoni* sporocyst mortality and the total antioxidant  
294 capacity of sporocysts were not normally distributed ( $P < 0.05$ ), and were subsequently analyzed  
295 using the Mann-Whitney test. The results of the ROS concentration assays in each mollusk strain  
296 were analyzed using the Mann-Whitney test. The Kolmogorov-Smirnov two-samples test was  
297 utilized to determine whether the ROS concentrations were similarly distributed in hemocytes from  
298 *BgBRE* and *BgGUA*.

299

300 **3. Results**

301 *3.1. Effect of  $\text{H}_2\text{O}_2$  on *S. mansoni* sporocysts*

302 Two different assays were conducted to test the effect of H<sub>2</sub>O<sub>2</sub> on the two strains of *S.*  
303 *mansoni* sporocysts (*SmBRE* and *SmGH2*) (Fig. 1). First, an LDH test was used to examine the  
304 cytotoxicity of H<sub>2</sub>O<sub>2</sub> on sporocysts of each strain. Our results revealed that the susceptibility to  
305 H<sub>2</sub>O<sub>2</sub> was significantly higher for *SmGH2* than *SmBRE* (Fig. 1A). When exposed to 200 μM H<sub>2</sub>O<sub>2</sub>,  
306 *SmGH2* sporocysts showed 25.8% cytotoxicity (i.e., 25.8% of the cells had lysed and released their  
307 LDH content), whereas no changes were observed for *SmBRE* at the same H<sub>2</sub>O<sub>2</sub> concentration (Fig.  
308 1A). However, although cell lysis occurred in *SmGH2*, the sporocysts were still alive at this  
309 concentration. To investigate possible between-strain differences in mortality, we next exposed  
310 sporocytes to increasing concentrations of H<sub>2</sub>O<sub>2</sub> and examined motility and the beating of the  
311 flame-cell flagella, which were taken as distinguishing between living and dead larvae. No  
312 difference between the two strains was observed until the concentration of H<sub>2</sub>O<sub>2</sub> reached 1,600 μM  
313 (Fig. 1B). At this concentration, 31.2% and 2.6% of the *SmGH2* and *SmBRE* sporocysts were dead,  
314 respectively; this difference is statistically significant (student's *t*-test; *P* = 0.017). These results  
315 suggest that *SmGH2* sporocysts are more susceptible to H<sub>2</sub>O<sub>2</sub> than *SmBRE* sporocysts.

316

### 317 3.2. The total antioxidant capacity of *S. mansoni* sporocysts

318 To investigate potential differences in the constitutive antioxidant abilities of sporocysts  
319 from *SmBRE* and *SmGH2*, we measured the cumulative antioxidant activities of these two strains  
320 (Fig. 2). Our results revealed that the antioxidant ability of *SmGH2* was significantly lower than that  
321 of *SmBRE* (approximately 13% less; Mann-Whitney test, *P* = 0.0001).

322

### 323 3.3. Reverse Transcription-quantitative PCR of ROS-scavenger expression among *S. mansoni* 324 strains

325 RT-qPCR was used to compare the expression of parasite antioxidant enzymes suspected to  
326 play key roles in the detoxification of host-induced oxidative stress (Table 1) (Guillou et al., 2007).  
327 Notably, Cu-Zn SOD (Smp\_176200.2) was found to be expressed at a significantly higher level in

328 *SmBRE* than in *SmGH2* (2.7-fold;  $P = 0.017$ ) (Fig. 3). In contrast, no difference was observed in the  
329 expression levels of glyceraldehyde-3-phosphate dehydrogenase (GAPDH, Smp\_056970.1), GST  
330 omega (Smp\_152710.1), GST 28 kD (Smp\_054160), GST 26 kD (Smp\_163610), glyoxalase II  
331 (Smp\_091010) or thioredoxin peroxidase (TPX, Smp\_158110) (data not shown).

332

### 333 3.4. Intracellular ROS measurements in single *B. glabrata* hemocytes

334 We monitored intracellular ROS levels in single hemocytes, using PBA. This method allows  
335 global ROS to be measured without interference from the reactive hydroxyl radical or  $H_2O_2$ . PBA  
336 fluorescent lifetimes were measured for 108 and 111 individual hemocytes originating from eight  
337 *BgBRE* and eight *BgGUA* snails, respectively. *BgBRE* hemocytes produced significantly (11.2%)  
338 more ROS than *BgGUA* hemocytes (Mann-Whitney test;  $P = 0.009$ ) (Fig. 4A). Fig. 4B shows the  
339 distribution of hemocytes from both strains according to their ROS concentrations, which were  
340 calculated from the ratio given in equation 1 (see Materials and methods section 2.8.2.). Although  
341 the cells from both *BgBRE* and *BgGUA* samples were distributed around the mean ROS  
342 concentration, their distributions were significantly different (Kolmogorov-Smirnov test,  $P =$   
343 0.012). Among the hemocytes producing more than 1.5-fold of the mean ROS concentration, 68.8%  
344 were from *BgBRE* strain, while only 31.2% were from *BgGUA*. Conversely, among the hemocytes  
345 that showed the lowest ROS concentrations ( $< 0.7$ -fold of the mean ROS concentration) 38.1%  
346 were from *BgBRE* and 62% were from *BgGUA* (Fig. 4B). By recording the fluorescent lifetimes of  
347 single cells loaded with PBA, we also obtained the relative concentrations of free and bound  
348 NAD(P)H (an indicator of metabolic change) in each cell. However there was no significant  
349 difference in the quantity of bound and free NAD(P)H (mean ratio = 0.60 for both strains; data not  
350 shown), suggesting that the strains had similar levels of metabolism. Thus, the only molecular  
351 difference observed between the two strains was the level of ROS production.

352

### 353 3.5. $H_2O_2$ production and release by *B. glabrata* hemocytes

354 We assessed H<sub>2</sub>O<sub>2</sub> production and secretion by hemocytes of both strains using Amplex  
355 Red. Fig. 5 shows the cumulative amount of H<sub>2</sub>O<sub>2</sub> constitutively released by hemocytes of each  
356 strain over 1 h. The maximum level of H<sub>2</sub>O<sub>2</sub> production was reached at 20 min for BgGUA and at  
357 40 min for BgBRE after addition of Amplex Red substrate. In total, BgBRE hemocytes produced  
358 significantly more (1.44-fold; mean value) H<sub>2</sub>O<sub>2</sub> than BgGUA hemocytes (student's *t*-test; *P* < 0.05)  
359 (Fig. 5).

360

### 361 3.6. *Biomphalaria glabrata* superoxide anion plasma content

362 To our knowledge, all spectrophotometric methods currently available for the determination  
363 of H<sub>2</sub>O<sub>2</sub> are based on the measurement of red or orange pigments, making these methods unsuitable  
364 for use on *B. glabrata* plasma samples, which are already tinted red by hemoglobin. Consequently,  
365 we used NBT to measure the amount of superoxide anion (O<sub>2</sub><sup>•-</sup>; a precursor of H<sub>2</sub>O<sub>2</sub>) produced in  
366 both strains. As shown in Fig. 6, at 3 h after addition of NBT BgBRE plasma contained  
367 significantly more (44% more) superoxide anion than BgGUA plasma (student's *t*-test; *P* = 0.0007).

368

### 369 3.7. Compatibility of sympatric and allopatric *S. mansoni*/*B. glabrata* combinations

370 Sympatric pairings of *S. mansoni* and *B. glabrata* originating from Brazil and Guadeloupe  
371 were previously shown to display different levels of compatibility that remained remarkably stable  
372 across laboratory generations (Théron et al., 2008). We first used dose-response curves obtained by  
373 challenging snails with increasing doses of miracidia to confirm that similar differences could be  
374 observed between our strains. At doses of 10 or more miracidia/snail, SmBRE/BgBRE showed an  
375 infection rate of 100%, while SmGH2/BgGUA had an infection rate of approximately half that, at  
376 around 55%. Interestingly, differences were also observed for the number of parasites (SpI) that  
377 develop within the snails. The infection intensity rose gradually as the challenge doses increased for  
378 SmBRE/BgBRE, reaching 16.18 ± 0.86 parasites/snail at the 50-miracidia dose. In contrast, the



379 infection intensity for *SmGH2/BgGUA* remained low regardless of the challenge dose, varying  
380 between  $1.6 \pm 0.20$  and  $3.2 \pm 0.64$  parasites/snail (Fig. 7).

381 When we tested the heterologous combinations, we found that the *SmBRE/BgGUA* pairing  
382 showed a substantial level of compatibility, with infection rates of 80-90% (not significantly  
383 different from the 100% achieved by the *SmBRE/BgBRE* pairing), but with lower parasite intensities  
384 ( $9.8 \pm 0.89$  for the 50-miracidia dose) compared with the sympatric combination ( $16.18 \pm 0.86$   
385 parasites/snail at the 50-miracidia dose). In contrast, the *SmGH2/BgBRE* combination showed very  
386 little infectivity, with infection rates  $< 6\%$  and  $\sim 1$  parasite/snail regardless of the challenge dose  
387 (Fig. 7).

388

389 *3.8. ROS, ROS scavengers and compatibility in sympatric and allopatric S. mansoni/B. glabrata*  
390 *combinations*

391 The above-described results indicated that levels of ROS and ROS scavengers were  
392 correlated in both sympatric combinations, with high-level ROS/ROS scavenger production in the  
393 Brazilian combination, but lower-level ROS/ROS scavenger production in the Guadeloupean  
394 combination. If high levels of *S. mansoni* ROS scavenger are correlated with better resistance of the  
395 intramolluskan stage of the parasite (as we hypothesized), we would expect *SmGH2* to have a  
396 relatively low ability to infect the allopatric *BgBRE* snails, while *SmBRE* would have a high ability  
397 to infect the allopatric *BgGUA* snails. This hypothesis was verified in our model, as shown in Fig.  
398 8.

399

#### 400 **4. Discussion**

401 Snail-schistosome compatibility and infection rates result from a complex interplay between  
402 the host's defense mechanisms and the parasite's infectivity strategies. Due to selective pressures  
403 exerted by the parasite on the host and vice versa, co-evolutionary dynamics may be observed  
404 (Janzen, 1980; Howard, 1991). Between-population or between-strain differences in the outcomes

405 of such evolutionary processes may be expected due to differences in the epidemiological and  
406 environmental conditions, and/or genetic architectures. Such differential selection patterns could  
407 explain, at least in part, the geographic and/or strain-specific compatibility variations seen in snail-  
408 schistosome interactions (Théron et al., 2008). At present, however, there is relatively little  
409 empirical evidence demonstrating reciprocal molecular adaptations in both host and parasite.

410 Here, we investigated the interaction between *S. mansoni* and the snail, *B. glabrata*, as this  
411 interaction is a popular model for the study of co-evolutionary dynamics (Beltran and Boissier,  
412 2008; Beltran et al., 2008; Bouchut et al., 2008; Roger et al., 2008a; Roger et al., 2008b; Roger et  
413 al., 2008c; Steinauer, 2009). We confirmed that there are different levels of compatibility between  
414 two geographic strains of *S. mansoni* and their sympatric snail hosts, *B. glabrata* (Fig. 7) that both  
415 have co-evolved independently. We compared the host oxidant and parasite antioxidant abilities  
416 that appear to form the core of the attack/defense interactions of these two pairings.

417 ROS are the main effectors of the snail immune system; they are highly reactive and can  
418 trigger irreversible cell damage. Indeed, ROS produced by the hemocytes of *B. glabrata* are known  
419 to play a crucial role in the killing of *S. mansoni* (Hahn et al., 2000; Hahn et al., 2001a, b; Bender et  
420 al., 2005; Bayne, 2009). Conversely, *S. mansoni* possess antioxidant systems capable of  
421 counteracting the ROS produced by their host's immune system. *Schistosoma mansoni* is exposed  
422 to ROS in both their intermediate (snail) and definitive (human or mammalian) hosts, and produce  
423 oxidative-stress scavengers in their excretory-secretory products (ESP) during all stages of their life  
424 cycle (Mei and LoVerde, 1997; Curwen et al., 2004; Zelck and Von Janowsky, 2004; Knudsen et  
425 al., 2005; van Balkom et al., 2005; Bernal et al., 2006; Dzik, 2006; Perez-Sanchez et al., 2006; Cass  
426 et al., 2007; Guillou et al., 2007; Mourao et al., 2009a; Wu et al., 2009). Therefore, the success or  
427 failure of host invasion by *S. mansoni* depends at least in part on its ability to defend itself against  
428 oxidative damage (Mourao et al., 2009a). In this system, therefore, ROS and ROS scavengers  
429 should be involved in a co-evolutionary arms race, and we would expect their respective production  
430 levels in sympatric host/parasite combinations to be closely related.

431 As previous studies have established that H<sub>2</sub>O<sub>2</sub> is the main ROS involved in killing *S.*  
432 *mansoni* sporocysts, probably due to its stability and capacity to cross cell membranes (Hahn et al.,  
433 2001b; Bienert et al., 2006), we studied the susceptibility of two strains of *S. mansoni* to H<sub>2</sub>O<sub>2</sub>. Our  
434 results showed a clear intrinsic difference between parasites isolated from two different geographic  
435 regions: the intramolluscan stages of Guadeloupean *S. mansoni* (*SmGH2*) were more sensitive to  
436 H<sub>2</sub>O<sub>2</sub> than those of the Brazilian strain (*SmBRE*) (Fig. 1). Moreover, we observed a difference in  
437 antioxidant potential between strains, with *SmGH2* displaying a lower level of antioxidant activity  
438 than *SmBRE* (Fig. 2). Thus, *SmBRE* has a more efficient antioxidant system, which would seem to  
439 explain its higher level of resistance to H<sub>2</sub>O<sub>2</sub>-mediated oxidative damage.

440 In order to identify the molecular pathways involved in these differential antioxidant  
441 properties, we investigated the strain-specific transcription levels of genes encoding various  
442 antioxidant enzymes, including GAPDH (Smp\_056970.1), GST omega (Smp\_152710.1), GST28  
443 (Smp\_054160), GST26 (Smp\_163610), glyoxalase II (Smp\_091010), thioredoxin peroxidase, and  
444 Cu-Zn SOD (Smp\_176200.2) (Guillou et al., 2007; Vermeire and Yoshino, 2007; Roger et al.,  
445 2008c; Mourao et al., 2009a; Wu et al., 2009). Among these candidates, only the Cu-Zn SOD  
446 mRNA displayed differential expression, with expression levels that were 2.7-fold higher in  
447 *SmBRE* than in *SmGH2* (Fig. 3). This finding is consistent with our protein-level results from a  
448 previous proteomic study (Roger et al., 2008c), and these observations collectively suggest that Cu-  
449 Zn SOD plays a key role in the antioxidant strategy of *S. mansoni*. The involvement of Cu-Zn SOD  
450 in ROS detoxification is a recurring and intriguing question, because it is capable of dismutating the  
451 superoxide anion (O<sub>2</sub><sup>•-</sup>) to produce H<sub>2</sub>O<sub>2</sub> (Zelck and Von Janowsky, 2004; Guillou et al., 2007;  
452 Mourao et al., 2009a). The hypothesis currently used to explain the role of *S. mansoni* Cu-Zn SOD  
453 in ROS detoxification is based on a suspected peroxidative function (Yim et al., 1993; Yim et al.,  
454 1996; Kim and Kang, 1997; Bayne et al., 2001). In short, it has been proposed that *S. mansoni* Cu-  
455 Zn SOD could use its own dismutation product (H<sub>2</sub>O<sub>2</sub>) to produce hydroxyl radicals (HO<sup>•</sup>) that are  
456 less toxic for sporocysts (Bayne et al., 2001).

457 In a co-evolutionary context, the between-strain differences in ROS susceptibility and  
458 antioxidant activity of these *S. mansoni* strains suggest that there could be comparable differences  
459 in the ROS production capabilities of the host snail strains. To test this hypothesis, we investigated  
460 ROS production by the two snail strains. First, we used a fluorescence-based method (Rharass et al.,  
461 2006) to investigate the hemocyte production of free-radicals such as nitric oxide and superoxide  
462 anion. This approach revealed that *BgBRE* snails produced more free radicals than *BgGUA* snails  
463 (Fig. 4A). Moreover, a distribution analysis of free-radical concentrations in single hemocytes  
464 showed that the cells producing higher concentrations of ROS came from *BgBRE* individuals, while  
465 those producing lower levels of free radicals were from *BgGUA* snails (Fig. 4B).

466 However, although our results revealed that global ROS production differed between  
467 *BgBRE* and *BgGUA*, oxidants can differ in their reactivity and efficient parasite killing requires  
468 that the host produce the right oxidant (Bayne et al., 2001). As previous studies have demonstrated  
469 the crucial role of hydrogen peroxide ( $H_2O_2$ ) in the killing of *S. mansoni* sporocysts (Hahn et al.,  
470 2001b; Goodall et al., 2004; Bender et al., 2005; Bender et al., 2007), we investigated potential  
471 differences in hemocyte  $H_2O_2$  production between the snail strains. Our results showed that  
472 hemocytes from *BgBRE* constitutively produced more  $H_2O_2$  than those from *BgGUA* (Fig. 5). We  
473 then examined the  $H_2O_2$  content of plasma from these snails. As technical restrictions make it  
474 impossible to directly measure  $H_2O_2$  in plasma, we measured the superoxide anion, which is a  
475 precursor of  $H_2O_2$  (Selkirk et al., 1998). Our results confirmed that *BgBRE* plasma contained  
476 significantly more superoxide anion than *BgGUA* plasma (Fig. 6). All of these data were obtained  
477 from hemocytes harvested from uninfected snails and without cell stimulation. Notably, no  
478 difference in ROS production was observed when these hemocytes were stimulated by the addition  
479 of phorbol 12-myristate 13-acetate (PMA) to culture medium (data not shown).

480 Taken together, our data show that: (i) the production of ROS in general and  $H_2O_2$  (the main  
481 ROS acting against *S. mansoni* sporocysts) in particular differ between the two snail strains; and (ii)  
482 this  $H_2O_2$  production seems to be correlated with the level of ROS scavengers produced by

483 sympatric parasites. *BgBRE* snails produce higher amounts of H<sub>2</sub>O<sub>2</sub> and interact naturally with  
484 *SmBRE*, which have better resistance against oxidative stress, while *BgGUA* snails produce less  
485 H<sub>2</sub>O<sub>2</sub> and are sympatric with *SmGH2*, which is more susceptible to ROS. If our hypothesis is  
486 accurate, therefore, we would expect our cross-infection experiments to reveal differences: (i) in the  
487 infective potential of our two *S. mansoni* strains; and (ii) in the resistance potential of our two *B.*  
488 *glabrata* strains.

489         Indeed, the results of the infection and cross-infection experiments showed significant  
490 differences in the infection rates and intensities (Fig. 7). The factors and mechanisms underlying  
491 these differences are not yet known, but may include historical epidemiological conditions,  
492 differential selective pressures in the transmission areas, genotypic diversities in the host and  
493 parasitic isolates, recognition mechanisms developed through the matching-phenotypes model, and  
494 intraspecific competition among sporocysts (for details, see (Théron et al., 1997; Théron and  
495 Coustau, 2005; Théron et al., 2008; Bech et al.). Notably, the host-parasite combination  
496 characterized by the higher infection rates and parasite intensities (*SmBRE/BgBRE*) was also  
497 characterized by a higher ROS-production capacity by the host and a higher ROS-scavenging  
498 ability by the parasite. In contrast, the host-parasite combination with lower infection rates and  
499 parasite intensities (*SmGH2/BgGUA*) showed lower ROS production by the host and lower ROS  
500 scavenging by the parasite (Fig. 8). These observations argue for the presence of reciprocal  
501 adaptation between the ROS and ROS scavenger traits. This was further supported by the results  
502 from our allopatric cross-infections. The *SmGH2* strain, which had co-evolved with its sympatric  
503 snail (*BgGUA*) to produce lower levels of ROS, could not effectively infect high-ROS-producing  
504 *BgBRE* snails (Figs. 7 and 8). Conversely, the *SmBRE* strain, which had co-evolved with a host that  
505 produced more ROS (*BgBRE*), could easily infect low-ROS-producing *BgGUA* snails (Figs. 7 and  
506 8). Interestingly, however, the infection success of *SmBRE* was lower for the allopatric combination  
507 than the sympatric pairing (Figs. 7 and 8), suggesting that the oxidative factors probably act in  
508 combination with other factors to determine the outcome of the *B. glabrata/S. mansoni* interaction.

509           Within hosts, immune effectors exert the main selective pressure on parasites (Loker and  
510 Adema, 1995; Damian, 1997). However, another factor that helps to define the interaction is the  
511 efficiency of parasite recognition by snail immune receptors, and the ability of the parasite to escape  
512 this recognition. We previously discovered a group of polymorphic antigens of *S. mansoni* (the *S.*  
513 *mansoni* polymorphic mucins, *SmPoMucs*) (Roger et al., 2008a; Roger et al., 2008b; Roger et al.,  
514 2008c), and recently showed that these antigens are recognized by diversified *B. glabrata* immune  
515 receptors (the fibrinogen-related proteins, FREPs) (Moné et al., 2010a). These reports on the  
516 molecular interactions underlying snail-schistosome compatibility suggest that co-evolutionary  
517 (reciprocal adaptation) processes probably occur through a combination of changes in general  
518 resistance (ROS/ROS scavengers) and more specific interactions (FREPs/*SmPoMucs*). In non-  
519 specific resistance/infectivity interactions involving density-dependant forces (e.g., the number of  
520 developing parasites within the host), co-evolution leads to global increases in the amount of  
521 attack/defense products, such as the interplay of ROS and ROS scavengers described herein. In  
522 highly specific genotype-by-genotype interactions, such as recognition/evasion processes, however,  
523 co-evolution leads to increases in the diversification and/or polymorphisms among specific  
524 molecules, as observed for FREPs and *SmPoMucs*.

525           Even if the success of infection is not exclusively based on the levels of ROS and ROS  
526 scavengers, our model of dynamic co-evolution predicts that a change in parasite virulence or host  
527 resistance would be associated with life history trade-offs (reallocation of resources), with increased  
528 production of a molecule under co-evolutionary pressure yielding indirect negative consequences  
529 for other functions (development, growth, fecundity, reproductive rate, etc.) (Green et al., 2000;  
530 Lohse et al., 2006; Forde et al., 2008). Indeed, this kind of trade-off has been observed in our  
531 model, as a previous study showed that cumulative cercarial production was two-fold higher for the  
532 *SmGH2/BgGUA* combination than for the *SmBRE/BgBRE* (Théron et al., 1997). This could  
533 indicate that *SmBRE* has made a tradeoff by investing in the production of ROS scavengers at the  
534 expense of producing cercariae.

535 In summary, host-parasite interactions are dynamic biological systems in which the host's  
536 defense mechanisms face the parasite's infectivity mechanisms, leading to a co-evolutionary arms  
537 race (Combes, 2000; Howard and Jack, 2007).

538 Developing correlation approaches to studying co-evolution have some limitations. Indeed  
539 the correlations between traits of interacting species cannot always provide unequivocal evidence  
540 for co-evolution. Reciprocity could also occur and an absence of correlated traits is not evidence for  
541 an absence of co-evolution (Nuismer et al., 2007; Nuismer et al., 2010; Yoder and Nuismer, 2010).  
542 Non-co-evolutionary mechanisms could explain correlations between the traits of interacting  
543 species. For example, the correlation could result from a colonization process in which a parasite  
544 species with new potential arrived in a new environment and is more well-adapted to the sympatric  
545 interacting species. In other interaction models correlated traits could evolve if the abiotic or biotic  
546 environments favour similar traits in both of the interacting species. For example, a biotic selection  
547 that affects only one of the interacting species can itself cause trait matching. This can occur if  
548 interactions have potent fitness consequences for only one of the species or if the outcome of  
549 interactions depends on the phenotype of only one of the species. These one-way interactions can  
550 generate correlations that are indistinguishable from those that evolve due to co-evolutionary  
551 processes (Nuismer et al., 2007; Nuismer et al., 2010; Yoder and Nuismer, 2010). In our model of  
552 interest *B. glabrata* could be infected by a lot of pathogens species (other than *S. mansoni*) that  
553 represent a selective pressure that could enhance snail ROS production. In this context,  
554 schistosomes for which the specificity for the intermediate snail host is very high will still succeed  
555 in infecting the snails, only if they are able to circumvent ROS by increasing their ROS scavenger  
556 production.

557 However, Nuismer et al. (2007, 2010) state that correlation could occur if interactions are  
558 mediated by a mechanism of phenotype matching such as what takes place for host-parasite  
559 interactions. This phenotype matching process was proposed for our *S. mansoni* / *B. glabrata* model  
560 of interest (Théron and Coustau, 2005).

561           Therefore whatever are the mechanisms involved in the apparition of trait correlation  
562 between two interacting species, our present results reveal the existence of phenotypic matching  
563 between host and parasitic strains in terms of their attack (ROS production) and defense (ROS  
564 scavenging) traits. To our knowledge, this work provides the first example of a clear link between  
565 the level of oxidant and antioxidant molecules possibly resulting from sympatric co-evolution, and  
566 provides supporting evidence for a field illustration of the Red Queen Hypothesis (Van Valen,  
567 1974) and its predictions of a functional trait in a metazoan host/parasite model. Detailed  
568 mechanistic studies will be conducted in multiple populations to fully confirm the link between  
569 correlated traits and the Red Queen context.

570

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579

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775



776 **Figure legends**

777

778 **Fig. 1.** Effect of hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) on *Schistosoma mansoni* sporocysts. (A) Cytotoxicity  
779 among *S. mansoni* sporocysts 2 h after exposure to different H<sub>2</sub>O<sub>2</sub> concentrations. The  
780 asterisk indicates a significant difference ( $P < 0.05$ ) in the cytotoxic effect of H<sub>2</sub>O<sub>2</sub> on *S.*  
781 *mansoni* Guadeloupean strain (*SmGH2*) versus *S. mansoni* Brazilian strain (*SmBRE*)  
782 sporocysts. (B) Percent sporocyst mortality after 4 h exposure to different H<sub>2</sub>O<sub>2</sub>  
783 concentrations. The asterisk indicates a significant difference ( $P < 0.05$ ) in the mortality  
784 rates of *SmGH2* versus *SmBRE* sporocysts.

785

786 **Fig. 2.** Constitutive total antioxidant capacities of *Schistosoma mansoni* Guadeloupean strain  
787 (*SmGH2*) and *S. mansoni* Brazilian strain (*SmBRE*) sporocysts. Values are expressed as  $\mu\text{M}$   
788 of antioxidant activity per 10  $\mu\text{g}$  of sporocyst proteins. The asterisk indicates a significant  
789 difference ( $P < 0.05$ ).

790

791 **Fig. 3.** Ratios of Zn-Cu superoxide dismutase (Zn-Cu SOD, Smp\_176200.2) transcript levels in the  
792 two strains of *Schistosoma mansoni* miracidia (Guadeloupean strain, *SmGH2* and Brazilian  
793 strain, *SmBRE*). Ratios were determined using real-time quantitative PCR and are expressed  
794 relative to the expression levels of 28s rRNA and  $\alpha$ -tubulin. The histogram represents the  
795 average values of duplicates  $\pm$  S.D. The expression ratio was calculated according to the  
796 formula:  $R = 2^{-(\Delta\text{Ct})}$ , where  $\Delta\text{Ct}$  represents  $\text{Ct}(\text{target gene}) - \text{Ct}(\text{constitutively expressed}$   
797  $\text{gene})$ .

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800

801

802 **Fig. 4.** Intracellular ROS measurements in single *Biomphalaria glabrata* hemocytes (A) Global  
803 reactive oxygen species (ROS) concentration in each snail strain. The histogram represents  
804 the ROS concentrations in arbitrary units (-fold mean) for the *Biomphalaria glabrata*  
805 Guadeloupean strain, *BgGUA* and Brazilian strain, *BgBRE*. The asterisk indicates a  
806 significant difference ( $P < 0.05$ ) in ROS production by hemocytes of the two snail strains.  
807 (B) ROS concentrations in hemocyte populations from *BgGUA* and *BgBRE* snails. The  
808 histograms represent the fluorescent lifetimes of 1-pyrenebutyric acid (PBA)-loaded  
809 hemocytes from eight each of *BgGUA* and *BgBRE*; 108 single hemocytes from eight  
810 *BgBRE* and 111 hemocytes from eight individuals of *BgGUA* snails were assessed. The  $x$   
811 axis represents the fluorescent lifetime in nanoseconds, while the  $y$  axis corresponds to the  
812 number of cells.

813

814 **Fig. 5.** Hydrogen peroxide ( $H_2O_2$ ) production by *Biomphalaria glabrata* hemocytes. Cumulative  
815 production of  $H_2O_2$  was measured using Amplex Red. The data are presented as the mean ( $\pm$   
816 S.D.) of Amplex Red absorbance at 570 nm ( $A_{570nm}$ ) per 45,000 cells over five replicates.  
817 The asterisk indicates a significant difference ( $P < 0.05$ ) in  $H_2O_2$  production from  
818 hemocytes of *B. glabrata* Guadeloupean strain, *BgGUA*, versus Brazilian strain, *BgBRE*.

819

820 **Fig. 6.** Constitutive superoxide anion plasma content in *Biomphalaria glabrata* Guadeloupean  
821 strain, *BgGUA*, versus Brazilian strain, *BgBRE*. The superoxide anion plasma content was  
822 assessed by spectrophotometric measurement (620 nm) of nitroblue tetrazolium (NBT)  
823 reduction. At 3 h after initiation of the reaction, the *BgBRE* plasma contained significantly  
824 more superoxide anion than that from *BgGUA* (the asterisk indicates a significant  
825 difference;  $P < 0.05$ ).

826

827 **Fig. 7.** Infection rates and intensities in sympatric and allopatric *Schistosoma*  
828 *mansoni/Biomphalaria glabrata* combinations. The percentage of snails infected and the  
829 intensity of infection: number of mother sporocysts (SpI) developed (*n* SpI) was measured  
830 after individual snails were challenged with different miracidial doses (1, 10, 20, 30 or 50  
831 miracidia (Mi)).

832

833 **Fig. 8.** Schematic representation of our reactive oxygen species (ROS)-based co-evolutionary  
834 hypothesis. The percentage of prevalence is indicated for each *Biomphalaria*  
835 *glabrata/Schistosoma mansoni* combination. The number of arrows represents the  
836 differential host oxidant (ROS) or parasite antioxidant (ROS scavenger) capabilities.  
837 *Biomphalaria glabrata* Brazilian strain, *BgBRE*, and Guadeloupean strain, *BgGUA*; *S.*  
838 *mansoni* Brazilian strain, *SmbRE*, and Guadeloupean strain, *SmGH2*.

839

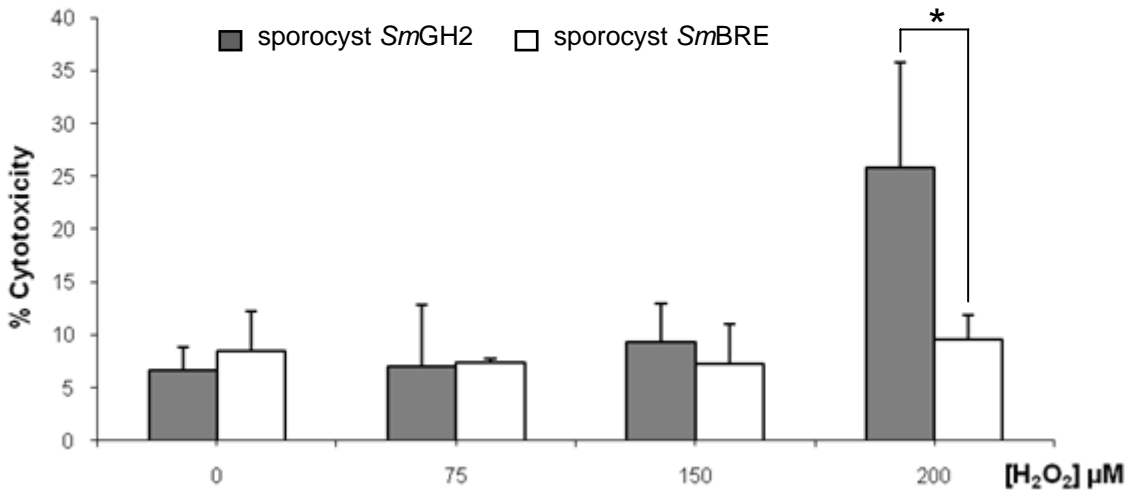
840

**Table 1**Primer sequences for *Reverse Transcription-quantitative PCR* in this study.

Gene Name and SchistoDB ID	Amplicon Length	Smp_scaffold	Forward primer (5' to 3')
Glyceraldehyde-3-phosphate dehydrogenase (GAPDH) Smp_056970	125	000155	TGGCCGTGGAGCGATGCAAA
Glutathione S-transferase omega Smp_152710	148	000154	ACAGCTCTAGTTGTCTGACCAAACA
Glutathione S-transferase 28 kD (GST 28) Smp_054160	128	000143	CGGACGCGGACGTGCTGAAT
Glutathione-S-transferase 26 kD (GST 26) Smp_163610	104	000249	GCAAAGCTGGTGGTTTGGGGC
Glyoxalase II Smp_091010	124	000428	ATGGCCTTCATTGCTTTGGACAGA
Thioredoxin peroxidase (TPX) Smp_158110	101		CAAAGGCCTTGTACAACCAACTC
Superoxide dismutase (SOD) Smp_176200.2	100	000615	AGTGGACTCAAGGCTG

Gene names are given according to the SchistoDB accession numbers (<http://schistodb.net/schistodb20/>). Their respective scaffolds are included in the table. Smp\_163610 primer sequences are given according to the mRNA sequence of the gene (XM\_002582157.1) due to inconsistency in the genome assembly.  $\alpha$ -tubulin and 28S primers sequences were previously published (Bahia et al., 2006; Roger et al., 2008a).

**A**



**B**

