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Emergence of Resistance to Atovaquone-Proguanil in Malaria Parasites: Insights From Computational Modeling and Clinical Case Reports

Gilles Cottrell, Lise Musset, Véronique Hubert, Jacques Le Bras, Jérôme Clain

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1 **TITLE**

2
3 **Emergence of resistance to atovaquone-proguanil in malaria parasites: insights from**
4 **computational modeling and clinical case reports**

5
6 Running title: Evolution of antimalarial drug resistance

7
8 Gilles Cottrell^{1,2}, Lise Musset^{3,4}, Véronique Hubert⁵, Jacques Le Bras^{1,2,5}, Jérôme Clain^{1,2,5}, and the
9 atovaquone-proguanil treatment failure study group⁶

10
11 ¹ UMR216, Institut de Recherche pour le Développement, 75006 Paris, France

12 ² UMR216, Faculté de Pharmacie, Université Paris Descartes, Sorbonne Paris Cité, 75006, Paris,
13 France

14 ³ Laboratoire de parasitologie, Institut Pasteur de Guyane, 97300 Cayenne, French Guiana

15 ⁴ Centre National de Référence du Paludisme, Laboratoire associé pour la région Antilles-Guyane,
16 97300 Cayenne, French Guiana

17 ⁵ Centre National de Référence du Paludisme, Laboratoire de Parasitologie-Mycologie, AP-HP,
18 Hôpital Bichat-Claude Bernard, 75018 Paris, France

19 ⁶ For a list of members please see the Acknowledgments

20
21 **Corresponding authors:**

22 Jérôme Clain
23 Address: UMR 216 IRD, Faculté de Pharmacie, Université Paris Descartes, 4 av de l'Observatoire,
24 75006 Paris, France
25 Tel: 00-33-1 70 64 94 33
26 Fax: 00-33-1 53 73 96 17
27 E-mail: jerome.clain@parisdescartes.fr

28
29 Gilles Cottrell
30 Address: UMR 216 IRD, Faculté de Pharmacie, Université Paris Descartes, 4 av de l'Observatoire,
31 75006 Paris, France
32 Tel: 00-33-1 53 73 15 07
33 Fax: 00-33-1 53 73 96 17
34 Email: gilles.cottrell@ird.fr
35

36 **ABSTRACT**

37 The usefulness of atovaquone-proguanil (AP) as antimalarial treatment is compromised by the
38 emergence of atovaquone resistance during therapy. However, the origin of the parasite mitochondrial
39 DNA (mtDNA) mutation conferring atovaquone resistance remains elusive.

40 Here, we report a patient-based stochastic model that tracks the intra-host emergence of mutations in
41 the multi-copy mtDNA during the few erythrocytic parasite cycles leading to the malaria febrile
42 episode. The effect of mtDNA copy number, mutation rate, mutation cost and total parasite load on the
43 mutant parasite load per patient was evaluated.

44 Computer simulations showed that almost any infected patient carried, after 4 to 7 erythrocytic cycles,
45 de novo mutant parasites at low-frequency, with varied frequencies of parasites carrying varied
46 numbers of mutant mtDNA copies. A large inter-patient variability in the size of this mutant reservoir
47 was found, explained by the different parameters tested but also by the relaxed replication and
48 partitioning of mtDNA copies during mitosis.

49 We also report seven clinical cases in which AP-resistant infections were treated by AP. These
50 provided evidences that parasitocidal drug concentrations against AP-resistant parasites were
51 transiently obtained within days following treatment initiation.

52 Altogether, these results suggest that each patient carries new mtDNA mutant parasites emerging
53 before treatment and that are destroyed by high starting drug concentrations; however, because the size
54 of this mutant reservoir is highly variable from patients to patients, we propose that some patients fail
55 to eliminate all the mutant parasites, repeatedly producing de novo AP treatment failures.

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58 INTRODUCTION

59 The recent emergence of *Plasmodium falciparum* malaria resistance to artemisinins in Southeast Asia
60 may lead to major public health consequences in a close future. There is an urgent need to identify
61 treatment regimens that maximize the therapeutically useful life span of current antimalarial drugs (1).
62 Among possible non-ACT available alternatives the role of atovaquone-proguanil (AP; initially
63 licensed as Malarone[®]) has been questioned (2-4). Atovaquone-proguanil is a popular prophylactic
64 drug and also shows high efficacy in the treatment of uncomplicated *falciparum* malaria in travellers.
65 Recently it has been used in the Greater Mekong Subregion to treat individuals detected as *P.*
66 *falciparum* carriers as part of a plan to contain artemisinin resistance (4). In addition, generic forms of
67 Malarone[®] have been recently licensed, and the marketing and use of AP could increase in endemic
68 settings (5).

69 Here, we focused on atovaquone resistance which develops easily during the treatment of
70 uncomplicated *P. falciparum* malaria using atovaquone as monotherapy (6). This high failure rate
71 prompted the introduction of the atovaquone-proguanil (AP) combination therapy. Atovaquone is a
72 potent inhibitor of the cytochrome *bc1* complex or complex III in the mitochondrial electron transport
73 chain (7). The addition of proguanil significantly increases the ability of atovaquone to collapse the
74 mitochondrial membrane potential (8), and also generates in vivo the metabolite cycloguanil which
75 antagonizes the parasite dihydrofolate reductase (*dhfr*) in the folate pathway (9-10). Resistance of *P.*
76 *falciparum* to atovaquone is primarily determined by one point mutation in the mitochondrial and
77 multi-copy *cytochrome b* (*cytb*) gene (11-12) which encodes a subunit of the cytochrome *bc1* complex.
78 In addition, *P. falciparum* parasites harbouring *dhfr* mutations exhibit cross resistance to both
79 antifolates pyrimethamine and cycloguanil (9, 13-14). Nowadays, a high rate of antifolate resistance is
80 found in *P. falciparum* parasites across major endemic areas (15). Hence, infecting parasites often
81 carry antifolate resistance and just a single evolutionary step –the acquisition of the *cytb* mutation– is
82 sufficient to make parasites resistant to both cycloguanil and atovaquone. Despite that the atovaquone
83 resistance mutation is not detected in endemic areas (16-18), about 1 in 100 non-immune travellers
84 returning to the UK and who took AP as treatment to cure a *P. falciparum* malaria episode had
85 treatment failure associated with atovaquone resistance (19). Genetic studies suggest that the
86 atovaquone resistance mutation evolves *de novo* during the primary infection or its treatment, being
87 then selected by AP treatment (20-22).

88 However, the mechanism underlying the rapid evolution of the *cytb* mutant parasites during AP
89 treatment remains elusive. Various hypotheses suggest a role for an increased rate of mitochondrial
90 DNA (mtDNA) mutations induced by atovaquone (23) and for pharmacokinetic-pharmacodynamic
91 considerations (5). Here another explanation was considered for the intra-host acquisition of
92 atovaquone resistance. We hypothesize that the multiple mtDNA copies per parasite along with the
93 complex replication of mtDNA (24-25) could favour a large mutational input before treatment.
94 Addressing experimentally the intra-host dynamics of mtDNA mutations is currently not possible in

95 the *P. falciparum* model, mainly because of its intractability, and modeling offers an opportunity to
96 explore this question.
97 Therefore, we developed for the first time a patient-based stochastic model that tracks the intra-host
98 emergence of malarial mtDNA mutations during the few rounds of asexual blood
99 stage reproduction leading to the malaria febrile episode and diagnosis. Briefly, it describes the
100 appearance of spontaneous mtDNA mutations and their propagation within replicating mitochondrial
101 genomes and parasites according to intra- and inter-cellular random drift, in absence of drug selection.
102 We evaluated the effect of several parameters on the intra-host frequency of mtDNA-mutated
103 parasites: the mtDNA mutation rate, the fitness cost associated to the mtDNA mutation, the number of
104 mtDNA copies per parasite, and the total parasite load per patient. Then, we reported clinical
105 evidences showing for the first time how AP-resistant parasites responded to AP treatment. Finally,
106 we integrated these computational and clinical new findings to propose a mechanistic framework
107 describing how atovaquone resistance emerges during malaria blood stages and how it translates into
108 AP treatment failure, and we discuss the implications of these results for drug usage in the field.

109 MATERIAL AND METHODS

110 We used a two-stage process: 1) we developed a model to calculate the probability that new mtDNA
111 mutations will be present among the malaria parasites at the time of treatment initiation; and 2) we
112 evaluated whether any such mtDNA-mutated parasites could survive AP treatment and recrudescence as a
113 new resistant infection. This two steps strategy follows a similar logic as the one used for nuclear
114 genes encoding resistance (26).

115 **1) The model.** The mathematical description of the model is provided in the Supplementary Text.

116 **Model framework.** The model simulates the replication and partitioning of parasitic mitochondrial
117 genomes within a replicating blood stage parasite lineage. It tracks the production and propagation of
118 parasite mtDNA mutations within a single infected human host, starting from the delivery of hepatic
119 parasitic forms into the blood to the time at which the patient will seek for medical care and treatment.
120 We assumed that: the infection takes place in a non-immune host; all parasites delivered from
121 hepatocytes into the blood have the wild type mitochondrial genotype; the mutation is a single
122 nucleotide replacement that arises through random and recurrent mtDNA replication errors during the
123 erythrocytic asexual parasite growth.

124 **Parasite growth.** We assumed that all initial parasites originated from a single release from the liver
125 and that each parasite infected a single erythrocyte. In each infected erythrocyte, the nuclear and
126 mitochondrial genomes of the parasite each are replicated through five consecutive endo-mitosis
127 (within one parasite cell) during one erythrocytic 48h-cycle, eventually leading to 32 daughter
128 parasites. Upon egress from the erythrocyte, each daughter parasite released in the blood has a
129 probability p_{surv} to survive and initiate a new erythrocytic cycle. We assumed parasite growth and
130 cycles to be synchronous within a single host infection.

131 **Replication and partitioning to daughter cells of mitochondrial genomes.** The detailed
132 mechanisms by which malaria mitochondrion and its genome replicate and are passed to daughter cells
133 are largely unknown, although important features have been described (24, 27). Hence we used a
134 sequence of events with minimum mechanistic assumptions. Eukaryotic organelle genomes, such as
135 mtDNA, undergo *relaxed* replication and partitioning, as compared to the stringent nuclear genome
136 (25, 28); it means that multiple mtDNA copies are replicated and partitioned randomly, with respect to
137 genotype.

138 We assumed that: i) each parasite contains one mitochondrion (29); ii) one mitochondrion
139 contains n copies of its genome (24); iii) n is constant within an infection; iv) at each mtDNA
140 replication, the template copies to be duplicated will be selected by n random draws with replacement
141 – allowing some mtDNA copies to be replicated several times while other copies not to be replicated.
142 This leads to a parasite containing one mitochondrion with $2n$ mtDNA copies; v) the mitochondrion
143 containing $2n$ mtDNA copies is then partitioned into two independent mitochondrial units, each
144 containing n mtDNA copies selected at random among the $2n$ mtDNA copies; vi) the
145 duplication/partitioning cycle of the mitochondrial genome repeats five times during one erythrocytic

146 48h-cycle; then, each of these $2^5=32$ mitochondrial units will constitute the single mitochondrion of
147 one of the 32 daughter parasites; vii) the resistance mutation arises spontaneously in one mtDNA copy
148 with a probability μ (per nucleotide per replication); because the atovaquone resistance mutation is a
149 single nucleotide substitution, we assumed that the probability of a resistant mutation to appear equals
150 the per nucleotide mitochondrial mutation rate ; during the course of the erythrocytic phase, n different
151 mutant parasite genotypes can be produced within a single host: parasites having from 1 to n of their n
152 mtDNA copies mutated.

153 We did not consider back mutation because its effect is unlikely to alter significantly the intra-host
154 frequency of the resistance mutation, specifically on the short time scale that our study addresses (1 to
155 7 cycles of 48hr intra-erythrocytic growth).

156 **Parasite definition according to mitochondrial genotype.** i) parasites having none of their n mtDNA
157 copies mutated were defined as *wild type* ; ii) parasites having from 1 to n-1 of their n mtDNA copies
158 mutated were defined as *heteroplasmic*; iii) parasites having all of their mtDNA copies mutated were
159 defined as *homoplasmic-mutant*; iv) the grouping of both heteroplasmic and homoplasmic-mutant
160 parasites was defined as *all-mutant* parasites.

161 **Mutation cost and fitness.** In some simulations, we assumed that, in absence of drug, carrying the
162 resistance mutation results in decreased parasite fitness (12, 30-31). We defined the fitness as the
163 proportion of daughter parasites of a given mitochondrial genotype that will succeed in invading new
164 erythrocytes. However, the mutation does not alter the probability of a mutant mtDNA copy to be
165 replicated or partitioned (25). In addition to the neutral situation (no decrease in fitness associated to
166 the mutation), two other situations were considered. First, the mutation is recessive relative to the
167 decrease in fitness: only homoplasmic-mutants have a decreased survival probability when compared
168 to any other genotype. Second, the mutation is dominant relative to the decrease in fitness: the survival
169 probabilities of heteroplasmic and homoplasmic-mutants are the same, and lower than the one of wild
170 type parasites. The recessive and dominant effects explored here represent the two ends of a spectrum,
171 in which the parasite fitness would be a function of the number of mutated mitochondrial genes.

172 **Input parameters.** i) the number of parasites delivered into the blood after the hepatic phase: $x =$
173 5×10^4 ; ii) the mtDNA mutation rate: $\mu = 10^{-9}$, 10^{-10} , and 10^{-11} /nucleotide/replication. To our
174 knowledge, there is no direct and unbiased estimate for the probability of a mtDNA change per
175 nucleotide per mtDNA replication in *P. falciparum*. Therefore, we have used very conservative values
176 based on values estimated in other species which range from 0.7×10^{-8} to 17×10^{-8} /nucleotide/mtDNA
177 replication (with one DNA replication/cell division (32-35)). In *P. falciparum* the nuclear mutation
178 rate was estimated to be 1.7×10^{-9} /nucleotide/48hr-generation during the blood stage growth (36); iii)
179 the parasite survival probability associated with the distinct mitochondrial genotypes (12, 37): wild
180 type, $p_{\text{surv}} = 12/32$; homoplasmic-mutant, $p_{\text{surv}_m} = 6/32$; heteroplasmic, $p_{\text{surv}_{ht}} = 12/32$
181 when the mutation cost is recessive and $p_{\text{surv}_{ht}} = 6/32$ when it is dominant; iv) the number
182 of mtDNA copies/parasite: $n = 5, 10, 20,$ and 40. This copy number was estimated to be about 20

183 copies/cell for *P. falciparum*, based on the analysis of a single parasite strain (24); v) the number of
184 erythrocytic 48h-cycles following delivery from the liver: from 1 to 7 (this corresponds from 2 to 14
185 days after the hepatic phase ; the median delay between onset of symptoms and treatment is 4 days in
186 imported *falciparum* malaria (38)).

187 **Model simulations.** Varying parameters were the mtDNA copy number, the mutation rate, the
188 mutation cost, and the number of erythrocytic 48h-cycles following parasite delivery from the liver.
189 Other parameters were fixed. For each combination of parameters tested, 20,000 simulations were run.
190 The simulations have been performed with R v 2.12.2 (R Foundation for Statistical Computing,
191 Vienna, Austria).

192 **2) Clinical case reports.** The French malaria reference center database was searched for late AP
193 treatment failures in which the recrudescence infections were treated again with AP. A total of 6,247
194 imported *P. falciparum* infections diagnosed and treated in France with AP were recorded by the
195 French malaria reference center, 2002-2012. Basic demographic and epidemiologic data, clinical and
196 parasitological informations, treatment, and history of travel and of malaria infections were collected
197 systematically. Pre- and post-treatment blood isolates were sent to the French malaria reference center
198 by French hospitals participating in the sentinel network for drug resistance and plasma drug testings.
199 Analyzed samples were obtained by blood collections required by the standard medical care for all
200 patients presenting with fever upon hospital admission in France.

201 **3) Ethics statement.** According to the French legislation, bio-banking and secondary use for scientific
202 purpose of human clinical remaining samples are possible as long as the corresponding patients are
203 informed and has not given any objection to them. Here, this requirement was fulfilled as the
204 information is given to every patient through the Hospital notice entitled “Information for patients”,
205 and no immediate or delayed patient opposition was reported by the hospital clinicians to the French
206 malaria reference center. Moreover, samples received at the French malaria reference center have been
207 registered and declared for research purpose as a bio-bank to both the Assistance Publique des
208 Hôpitaux de Paris and to the French National Institute of Health Survey. No institutional review board
209 approval is required according to the French legislation (article L. 1111-7 du Code de la Santé
210 Publique, article L. 1211-2 du Code de Santé Publique, articles 39 et suivants de la loi n° 78-17 du 6
211 janvier 1978 modifiée en 2004 relative à l’informatique, aux fichiers et aux libertés). Samples used
212 were not anonymized.

213 **4) Molecular analysis.** Parasite genomic DNA was extracted from whole blood, thin or thick blood
214 smears, and plasma. The *cytb* gene was sequenced directly from PCR products to genotype the codon
215 *cytb*²⁶⁸ that associates with atovaquone resistance. Five nuclear microsatellite locus (TAA81, TAA87,
216 PfPK2, Ara2, and TAA60) dispersed on 5 different *P. falciparum* chromosomes were genotyped by
217 capillary electrophoresis to determine the nuclear genetic background associated with each of these
218 parasite isolates. All methods were as previously described (22). The codons 51, 59 and 108 of the

219 *dhfr* gene associated with cycloguanil resistance were genotyped either by PCR-RFLP as described in
220 (39) or by direct sequencing of PCR products.

221 **5) Estimation of the parasite reduction ratio for atovaquone-proguanil/cycloguanil-resistant**
222 **parasites.** To evaluate the intrinsic *in vivo* efficacy of AP treatment on drug resistant parasites, we
223 measured the parasite reduction ratio (PRR) which is defined as the fractional reduction in parasite
224 number per asexual life cycle (i.e. 48h) or time unit (day) during the treatment (40). The parasite
225 reduction ratio is similar to the killing rate induced by a specific treatment. A parasite reduction ratio
226 of 50 means that 1 out of 50 parasites survive to drug treatment per asexual life cycle. Based
227 on the clinical cases in which infected patients carrying AP-resistant parasites were treated with AP
228 and for which two non-negative and consecutive blood parasite counts were recorded, we estimated
229 the PRR as being equal to $(P_0/P_t)^{2/t}$, where P_0 and P_t are parasite loads at days 0 and t, respectively (41-
230 42).

231 **6) Estimation of the minimum time required to clear all the cryptic *de novo* mutant parasites**
232 **from an infection.** Using the intra-host distribution of mtDNA-mutated parasites generated through
233 20,000 simulated infections, we estimated the minimum time (T, in days) during which blood drug
234 concentrations should equal or exceed the minimum parasitocidal concentration (MPC^{APR}) to clear all
235 the cryptic mtDNA-mutated parasites. We assumed that the PRR of AP-resistant parasites (PRR^{APR}) is
236 constant and that AP-resistant parasites are killed at the same rate whether they represent the minority
237 or the dominant population within the infection. An estimate for T can be obtained using the following
238 formula: $T = 2 \times \ln B_m / \ln(PRR^{APR})$, where B_m is the mutant parasite load per infection (41). We
239 estimated T for simulations obtained with a recessive fitness cost, copy number = 20 and mutation rate
240 = 10^{-10} /nucleotide/replication.

241

242 RESULTS

243 **A model of mtDNA evolution for the pre-treatment phase.** We modeled the evolution of *de*
244 *novo* mtDNA mutations that arose during the intra-host expansion of replicating *P.*
245 *falciparum* erythrocytic forms in the absence of drug selection. After the delivery of parasites from the
246 liver into the blood stream, the mean total parasite load per patient multiplied by ~12-
247 times/erythrocytic 48hr-cycle and reached about 1.5×10^{11} parasites at the 6th cycle (corresponding to
248 12 days after the hepatic phase). Assuming a volume of 5 liters of blood per patient and an erythrocyte
249 concentration of $5 \times 10^{12}/L$, this translates to 0.6% of total host erythrocytes being infected. During this
250 intense replicating phase, random recurrent mtDNA mutations occurred and then replicated and
251 segregated according to random drift (combined or not with negative selection) within daughter
252 mitochondrial genomes and parasites (Fig. 1). This produced heteroplasmic parasites and ultimately
253 homoplasmic-mutant parasites, having all of their mtDNA copies being mutated (Fig. 1A). For our
254 reference model (neutral mutation, 20 mtDNA copies per parasite, and a mtDNA mutation rate of 10^{-10} /
255 nucleotide/replication), all-mutant parasites (having at least one mtDNA copy being
256 mutated) appeared on average at the first erythrocytic cycle with a mean frequency of $\sim 4 \times 10^{-9}$ all-
257 mutant parasites/infection which then slightly increased with additional 48hr-cycles to reach ~ 75 times
258 the mutation rate at the 6th cycle (Fig. 1B). Homoplasmic-mutant parasites appeared on average at the
259 3rd cycle and then increased in frequency to a mean value close to the mutation rate at the 6th cycle
260 (Fig. 1B). At the 6th cycle the composition of the mtDNA mutant parasite population per patient was
261 found to be complex, each patient harbouring at varied and low frequencies an array of genotypically
262 distinct mutant parasites defined by the number of mtDNA copies being mutated (Fig. 1C and 1D).
263 Next, we focused on the intra-host distribution of mutant parasites at the 6th cycle when the mean total
264 parasite load per patient was $\sim 1.5 \times 10^{11}$. The number of mtDNA copies per parasite had opposite
265 effects on the intra-host distribution of homoplasmic- and all-mutant parasite load (Fig. 2A and 2B):
266 the larger the copy number, the larger is the number of all-mutants but the lower is the number of
267 homoplasmic-mutants per infection. The size of both the homoplasmic- and all-mutant populations
268 increased with the mutation rate (Fig. 2C and 2D) and with the total parasite load per
269 patient (Fig. 2E and 2F). Finally, the fitness cost of the resistance mutation altered the number of
270 mutant parasites per infection in a very expected way when compared to a neutral
271 model (Fig. 2G and 2H): a recessive mutation cost did not alter the all-mutant population but was
272 associated with a slight decrease in the number and the variability of the homoplasmic-mutant
273 population, whereas a dominant mutation cost markedly decreased both all- and homoplasmic-mutant
274 population size. Simulations also revealed as a general trend the right skewed distribution of mutant
275 parasites per infection (Fig. 1D and Fig. 2). Highly relevant to the outcome of malaria treatment,
276 infections containing mutant parasites before treatment were extremely frequent (Fig. 3): even when
277 considering a conservatively low mtDNA mutation rate of 10^{-10} /nucleotide/replication and parasite
278 burden of 1.2×10^{10} /body ($\sim 0.05\%$ of total host erythrocytes being infected), 100% of simulated

279 infections contained at least one parasite having at least one mtDNA copy being mutated
280 (corresponding to the 5th cycle in Fig 3A; this proportion decreased to 93% for 10⁹ parasites per host).
281 Infections containing at least one homoplasmic-mutant parasite were also frequent: 1.4%, 16.3%, and
282 88.3% at the 5th, 6th and 7th cycle, respectively. The proportion of patients carrying high loads of
283 mutant parasites was largely altered by the total parasite load per patient (Fig. 3A and 3B).
284 In summary, whatever the parameter values tested here, all simulations shared three essential
285 results: 1) the mtDNA resistance mutation could occur *de novo* and propagate in most infected host
286 during the erythrocytic parasite expansion phase before a treatment has been initiated; 2) each
287 patient harboured a complex reservoir of cryptic mutant parasite populations, with varied frequencies
288 of parasites having varied numbers of their mtDNA copies being mutated ; 3) a marked inter-patient
289 variation in the size of this cryptic mutant reservoir was found, even for a unique set of parameters;
290 and 4), a small fraction of the patients carried a high load of mutant parasites. The very high rate of
291 patients found to carry mtDNA-mutated parasites would suggest a very high rate of AP treatment
292 failure, unless the current AP regimen retains therapeutic efficacy towards mtDNA-mutated parasites,
293 thereby limiting the extent of treatment failure. Therefore we sought for evidences showing how AP-
294 resistant parasites responded to AP therapy.

295 **How do atovaquone-proguanil/cycloguanil-resistant parasites respond to AP treatment: clinical**
296 **observations.** Within the ~6,200 *P. falciparum* imported malaria cases that were treated with AP and
297 reported to the French malaria reference center between 2002 and 2012, we identified 7 cases in which
298 recrudescing AP-resistant infections were treated again with AP (Table 1). Full case reports are
299 described in Supplementary Text. These clinical observations were backed up with the genotyping of
300 atovaquone and cycloguanil resistance markers and of microsatellites to assess the identity of the pre-
301 treatment and post-treatment recrudescing parasites. For each patient, the genetic data showed the
302 selection after the first AP treatment of mutant *cytb*²⁶⁸ parasites having a nuclear genetic background
303 identical to the one of parasites from the primary infection. This is consistent with our earlier findings
304 (11-12). For five of these patients (patients P1 to P5) the treatment of the AP-resistant infections with
305 another cure of AP was associated with a late failure with parasites recrudescing 8 to 30 days after
306 therapy initiation (mean: 20.6 days), whereas for the other two patients the treatment was altered at
307 day 3 and 5 although their initial parasitemia had significantly decreased. For five cases (P3 to P7),
308 evidence for AP-resistant parasite clearance within days following treatment was obtained from
309 microscopic examination of blood smear, and for three cases (patients P1, P4 and P7) no standard
310 antimalarial drug in addition to atovaquone, proguanil, and cycloguanil was detected in the blood
311 during treatment (these informations were not available for the other cases).
312 Based on the patients P3, P6, and P7 for which two non-negative and consecutive blood parasite
313 counts were available (at day-0 and day-3 or day-5; table 1), we estimated the parasite reduction ratio
314 for AP-resistant infections (PRR^{APR}) during the first days of AP therapy to be 116, 10, and 30 (mean:
315 52), respectively. Altogether, these clinical findings showed that some AP-resistant parasites can be

316 eliminated by AP as long as drug blood concentrations are maintained above a yet unknown threshold
317 value, which we defined as the minimum parasitocidal concentration (MPC^{APR}).

318 **Estimation of the minimum time required to clear the cryptic mtDNA-mutated parasites.** We
319 estimated the time (T) during which drug concentrations in the blood should exceed or equal the
320 MPC^{APR} to clear from any host all the cryptic mutant parasites that emerged during the primary
321 infection. Assuming a constant PRR^{APR} of 50, $T = 0.51 \ln B_m$ (where B_m is the mutant parasite load per
322 patient). In hyperparasitemic patients carrying about 1.8×10^{12} parasites (~7% of total host erythrocytes
323 being infected), the maximum load of homoplasmic-mutant parasites found before treatment among
324 20,000 simulations was 176,395 parasites/host (simulation parameters: recessive mutation, mutation
325 rate = 10^{-10} /nucleotide/replication, mtDNA copy number = 20). The MPC^{APR} should then be
326 maintained during at least 6.2 days to ensure the complete elimination of this homoplasmic-mutant
327 intra-host population (Table 2). When considering mutant parasites having at least 1/20 or 10/20 of
328 their mtDNA copies being mutated, drug blood concentrations equal to or larger than the MPC^{APR}
329 should be maintained during a longer length of time to produce similar treatment efficacy. In non
330 hyperparasitemic patients (for example carrying about 1.5×10^{11} or 1.2×10^{10} parasites which correspond
331 to ~0.6% and ~0.05% of total host erythrocytes being infected), the MPC^{APR} should be maintained for
332 shorter time to clear all the mutant parasites (Table2).

333

334 DISCUSSION

335 We report here new findings that help to explain the easy and repeated evolution of mtDNA mutations
336 conferring atovaquone resistance and the high rates of atovaquone and AP treatment failures in non or
337 little immune patients (6, 19, 21, 43). Firstly, our work explores for the first time the intra-host
338 dynamics of malarial mtDNA mutations through stochastic modeling at the micro-evolutionary time
339 scale, id est during few erythrocytic parasite cycles. Computational data show that almost any primary
340 malarial infection in a non-immune human host carries a cryptic population of *de novo* mtDNA-
341 mutated parasites at the time of malaria diagnosis, before a treatment has been initiated. Given the
342 large parasite load per human body at malaria diagnosis (the median peripheral parasitemia of 0.4% in
343 travellers roughly corresponds to 1.2×10^{11} parasites per body) and that each parasite contains ~ 20
344 copies of mtDNA (24), the intra-host population size of mtDNA molecules grows to extremely large
345 values. This provides multiple opportunities for random mtDNA mutations to occur within each
346 infected host. The extremely low intra-host frequency of these *de novo* mtDNA mutations (\sim a median
347 of 1 to 10 times the mutation rate, according to total parasite load per patient, Table S1) precludes their
348 detection in patient blood samples with standard molecular techniques. Indeed, in hyperparasitemic
349 patients carrying $\sim 1.8 \times 10^{12}$ parasites and assuming 5 liters of blood per patient, the model indicated
350 that a mutant allele is present at an intra-host median frequency of $\sim 10^{-9}$ (simulation parameters:
351 recessive mutation, mutation rate = 10^{-10} /nucleotide/replication, mtDNA copy number = 20) which
352 translates to ~ 3 mutant allele copies/10 mL of blood (this increased to 36 allele copies/10 mL of blood
353 in top 1% of patients with high mutant parasite burden). This is consistent with genetic tests that failed
354 to detect the resistance mutation in the pre-treatment blood samples (19-21, 44-45), even using a
355 mutant-enrichment method (22). Highly sensitive methodologies based on next-generation sequencing
356 which can detect one mutant copy among about 10^6 - 10^7 wild-type copies could be helpful in the future
357 to test our computational results (46-47). In summary, the model findings point to spontaneous
358 mtDNA mutations occurring before treatment as a primary source of atovaquone resistance mutations.
359 And we consider it is not necessary to invoke a mutagenic effect of atovaquone (see Supplementary
360 Text for further discussion). This proposal is in line with findings in *Mycobacterium tuberculosis*
361 reporting the *de novo* acquisition of multidrug resistance before treatment as a risk factor for treatment
362 failure (48), and with mathematical modeling studies in several pathogens (48-51). Secondly, we
363 report novel clinical cases showing that the drug blood concentrations attained during the first days of
364 AP therapy are high enough to clear some AP-resistant parasites. We provide an estimate for the
365 PRR^{APR} (mean: 52 ; see Supplementary Text for discussion associated with this estimate), not
366 markedly different from the values obtained for AP-sensitive infections which ranged from 46 to 261
367 in non-immune adults (52). The reasons for this finding remain elusive but we propose several
368 hypotheses. At high concentrations, atovaquone can inhibit both wild type and mutant cytochrome *b*
369 (12) and was found also to be a more general ubiquinone antagonist, inhibiting the substrate-
370 ubiquinone reductases of the respiratory chain distinct from the cytochrome *bcl* complex (53). In

371 addition, it is the net effect on parasite killing of high concentrations of atovaquone, proguanil and
372 cycloguanil in combination that should be considered, an issue raised recently also for chloroquine
373 (54). An estimate for the MPC^{APR} is yet to be determined and the MPC^{APR} will likely be a complex
374 interplay between atovaquone, proguanil and cycloguanil blood concentrations and the threshold
375 number of mutated mtDNA copies per parasite that confers resistance to atovaquone.
376 Altogether, our computational and clinical results support the following *scenario* regarding *de novo*
377 AP treatment failures. AP treatment success relies in almost any patient on the clearance of cryptic
378 mtDNA-mutated parasites that evolved during the erythrocytic growth phase of the primary infection.
379 Clearance of mutants must occur within the first days of AP treatment, when drug blood
380 concentrations are the highest and exceed the MPC^{APR} . We then refer to the time during which drug
381 blood concentrations exceed or equal the MPC^{APR} as the window of mutant prevention. We suggest
382 that the therapeutic margin of the current AP regimen, especially in the context of non-supervised
383 treatment, is not wide enough to clear all the cryptic mutant parasites in any patient, hence producing
384 repeatedly *de novo* AP treatment failures. The main reasons for this, based on our data and the
385 literature, could be the inter-patient variability of the following parameters: the width of the mutant
386 prevention window and the number of *de novo* mtDNA-mutated parasites that the treatment has to
387 destroy. With regards to the width of the mutant prevention window, a major source of variability is
388 obviously the large inter-patient variability in atovaquone blood concentration which is driven by the
389 slow and limited absorption of the drug (55-56). In addition, this is likely made worse in the context of
390 non-supervised treatment because of potential vomiting and/or poor compliance with the 3-day course
391 of treatment. Another source of variability could be the level of atovaquone resistance conferred by the
392 *cytb*²⁶⁸ mutation which will likely alter the MPC^{APR} , hence the width of the mutant prevention window.
393 With regards to the *de novo* mutant parasite load, the model revealed a very large inter-patient
394 variability. This variability was contributed largely by some type of random drift specifically
395 associated with mtDNA replication and partitioning during mitosis and also by the inter-patient
396 variability in total parasite load at diagnosis. As shown also by modeling studies for nuclear mutations
397 (51, 57), the larger is the total parasite load, the larger the *de novo* mutant load, and the longer it will
398 take to eliminate all *de novo* resistant parasites from an infection. This is consistent with our clinical
399 data and those already published (19-21, 45, 58-60), which altogether showed that 17 of 20 patients
400 experiencing *de novo* AP treatment failure presented with parasitemia at diagnosis close to or larger
401 than 0.4% (corresponding to the median peripheral parasitemia observed at the time of *P. falciparum*
402 malaria diagnosis in travellers returning to France and the UK (38, 61); mean parasitemia: 2.4%,
403 median: 1.4%, min: <0.005%, max: 13%; Table S2). Controlled studies will be needed to confirm this
404 observation. Additional sources of mutant load variability could be contributed by the mtDNA
405 mutation rate (48, 62) and mtDNA copy number, but whether those parameters vary substantially
406 between *P. falciparum* clinical isolates remains to be established.

407 Here, we did not consider mutations occurring earlier during the primary infection, *id est* during the
408 liver phase (63). This would however even increase the mutant load and the probability of a patient to
409 carry mutant parasites. Regarding the physical mechanisms controlling how malaria organelles and
410 their genome replicate and are passed to daughter cells, this remains a largely unexplored area. During
411 one erythrocytic 48hr-generation, the malarial mitochondrion elongates from a single organelle, then
412 branches and ultimately divides to create multiple daughter organelles (27). Our model assumes 5
413 consecutive rounds of random mtDNA replication/partitioning during one erythrocytic generation, in
414 which each mtDNA copy behave as an independent unit of replication. We argue that this model
415 mimics the effects of both the likely separation of mtDNA molecules within the elongating and
416 branching mitochondrion and the random drift associated with the mtDNA replication (24-25, 27).
417 Variations of this standard model can be envisaged, such as a more panmictic behaviour of mtDNA
418 copies (24), but we do not expect they will produce qualitatively very different results. In its current
419 version, our model is not designed to evaluate the long term evolution of mitochondrial genetic
420 diversity, either within a single-host infection that would last for several weeks or months or within an
421 entire malaria parasite population across multiple rounds of host/vector transmission. This would
422 require to consider back mutation and host-specific immunity and to take into account the large
423 heterogeneity and complexity of parasite transmission (26, 64). Altogether, our model provides, to our
424 knowledge, the first framework to study the intra-host early evolution of malarial mtDNA mutations.
425 It may provide a valuable addition to the current modeling methodologies that rather focus on nuclear
426 mutations. Specifically, it could be helpful to study the evolution of mitochondrial genes whose
427 products may be targeted by new antimalarial drugs, an area of intense research (65-68).

428 It is currently not clear how many mutant *cytb* copies per parasite are necessary to confer high-grade
429 atovaquone resistance. Our model did not simulate the fate of parasites having distinct mtDNA
430 genotypes (wild type, heteroplasmic, homoplasmic-mutant) once treatment has been initiated, hence
431 under drug selection. Experiences in yeast show that the effect of drug selection will largely
432 overshadow the one of random drift (69). We speculate that once AP treatment has started,
433 intercellular selection within the host will likely favour the growth of those parasites having the largest
434 proportions of their mtDNA copies being mutated. In case some heteroplasmic genotypes could
435 survive to AP treatment, the combination of random drift and strong drug selection would result in a
436 progressive shift in the mutant parasite population, with the progressive accumulation of
437 homoplasmic-mutant parasites (as shown experimentally in yeast (69); see also Supplementary Text).

438 Our model for the emergence of atovaquone resistance suggests that the partner drug -here proguanil
439 together with its active metabolite cycloguanil- plays a critical role in preventing the escape of *de novo*
440 mtDNA mutant parasites. This is consistent with the observation that most atovaquone resistance
441 mutations reported to date were found to emerge in parasites carrying a mutant *dhfr* gene (Table S2).

442 Controlled studies with a large patient cohort will be necessary to confirm these observations.
443 Speculating on the computational model findings and the high rate of *de novo* AP treatment failure
444 reported in travellers, we warn against the risk of the rapid emergence of atovaquone resistance if AP
445 is used massively with the current regimen in transmission areas where people are little- or non-
446 immune (2-3). This could be particularly rapid in the multiple areas where mutant *dhfr* gene is found
447 at a high rate in parasite populations (15), as a consequence of a long history of sustained use of the
448 antifolate pyrimethamine.

449 The framework proposed here suggests several ways by which to delay the clinical emergence of AP
450 resistance. A first strategy could be to extend the window of mutant prevention by maintaining
451 atovaquone and proguanil/cycloguanil blood concentrations at a higher level and for a longer period of
452 time than those achieved with the current AP dosage regimen. The benefit of a more aggressive
453 chemotherapy in reducing the chance of *de novo* resistance selection has been recently questioned (1,
454 70). However, the clinical findings that AP at high drug blood concentrations remains potent on AP-
455 resistant parasites suggest such a strategy merits further attention. A second (and possibly
456 complementary) strategy that we favour would be to minimize the number of *de novo* mutant parasites
457 that AP has to destroy. This could be achieved through combination therapy, employing an additional
458 drug equally potent against AP-sensitive and AP-resistant parasites. For example, the triple
459 combination of artesunate-atovaquone-proguanil proved to be very efficient for the treatment of
460 malaria in pregnancy and of uncomplicated malaria (71-73). Also, the use of AP could be restricted to
461 treat infections from endemic areas where the frequency of mutant *dhfr* genes is low. Finally, an
462 important prediction of our model is that patients with higher parasite burden at diagnosis face an
463 increased risk for carrying larger *de novo* mutant parasites. Then the use of AP as treatment could be
464 restricted to patients with lower parasitemia at diagnosis.

465 In summary, we report new computational and clinical findings describing the intra-host evolution of
466 mtDNA mutations conferring atovaquone resistance. The mechanistic framework proposed here helps
467 to explain the repeated evolution of *de novo* AP resistance, and it could help policy makers in
468 designing AP-containing treatment regimens that delay the clinical emergence of atovaquone
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474 Laboratoire de Parasitologie-Mycologie, AP-HP, Hôpital Bichat-Claude Bernard, 75018 Paris), Céline
475 Maréchal (Centre National de Référence du Paludisme, Laboratoire de Parasitologie-Mycologie, AP-
476 HP, Hôpital Bichat-Claude Bernard, 75018 Paris), Pascal Houzé (Laboratoire de Biochimie, AP-HP,
477 Hôpital Saint Louis, 75010 Paris), Marc Thellier (Centre National de Référence du Paludisme,
478 Laboratoire de Parasitologie-Mycologie, AP-HP, Hôpital La Pitié-Salpêtrière, 75013 Paris), Eric
479 Kendjo (Centre National de Référence du Paludisme, Hôpital La Pitié-Salpêtrière, 75013 Paris),
480 Liliane Ciceron (Centre National de Référence du Paludisme, Hôpital La Pitié-Salpêtrière, 75013
481 Paris), Sophie Matheron (Maladies infectieuses et tropicales, AP-HP, Hôpital Bichat-Claude Bernard,
482 75018 Paris), Anne Delaval (Centre Hospitalier Intercommunal Robert Ballanger, 93602 Aulnay-sous-
483 Bois), François Martin-Barbaz (Centre Hospitalier de Niort, 79021 Niort), Bernadette Buret
484 (Laboratoire de Biologie, Centre Hospitalier de Niort, 79021 Niort), Gianandrea Borgherini (Maladies
485 Infectieuses, Groupe Hospitalier Sud Réunion, 97448 Réunion), Sandrine Picot (Laboratoire de
486 Bactériologie-Parasitologie, Groupe Hospitalier Sud Réunion, 97448 Réunion), Dieudonné Bemba
487 (Laboratoire de Microbiologie, AP-HP, Hôpital Jean Verdier, 93140 Bondy), Isabelle Poilane
488 (Laboratoire de Microbiologie, AP-HP, Hôpital Jean Verdier, 93140 Bondy), Thanh-Van Trieu
489 (Urgences Pédiatriques, AP-HP, Hôpital Jean Verdier, 93140 Bondy), Marie Belloy (Centre
490 Hospitalier Intercommunal Robert Ballanger, 93602 Aulnay-sous-Bois), Martin Danis (Centre
491 National de Référence du Paludisme, Laboratoire de Parasitologie-Mycologie, AP-HP, Hôpital La
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712 **Figure legends**

713

714 **Figure 1. Dynamics and loads of mtDNA mutant parasites per human host.** Data are from
715 20,000 simulations, with one simulation representing one human infection. **A**, triangles
716 represent homoplasmic-mutant parasites and circles represent all-mutants (either
717 heteroplasmic or homoplasmic-mutants); plain and dashed lines represent the median and the
718 99.5th percentile, respectively. **B**, triangle and circle symbols represent homoplasmic-mutant
719 and all-mutants parasites, respectively. **C** and **D**, data are from simulations stopped at the 6th
720 erythrocytic 48h-cycle following parasite delivery from the liver (corresponding to a mean
721 total parasite load per host of 1.5×10^{11}). The load of mutant parasites per host is shown,
722 according to the number of mtDNA mutant copies per parasite. **C**, each line (either plain or
723 dashed) represents one simulated infected host randomly chosen among 20,000 simulations.
724 Five simulations are shown. **D**, box-plots show the median and inter-quartile range (IQR), and
725 the bottom and top whiskers show the lowest data still within 1.5xIQR of the lower quartile
726 and the highest data still within 1.5xIQR of the upper quartile, respectively. Outlier values are
727 shown as dots. There is no mutation cost, the mtDNA copy number is 20, and the mutation
728 rate is 10^{-10} /nucleotide/replication in all the simulations presented here.

729

730 **Figure 2. Load of mtDNA mutant parasites per human host according to different**
731 **parameters.** Data are from 20,000 simulations, with one simulation representing one infected
732 host. **A, C, E and G:** refer to all-mutant parasites, *id est* having at least one of their n mtDNA
733 copies being mutated. **B, D, F and H:** refer to homoplasmic-mutant, *id est* parasites having all
734 of their n mtDNA copies being mutated. **E and F**, at the 5th, 6th and 7th erythrocytic 48hr-
735 cycles, there is a mean number of 1.2×10^{10} , 1.5×10^{11} , and 1.8×10^{12} parasites per host in our
736 simulations, respectively. Except if differently stated, mutation rate is 10^{-10}
737 /nucleotide/replication, there is no resistance mutation cost (neutral), the mtDNA copy
738 number is 20, and the parasite load per host is 1.5×10^{11} (corresponding to the 6th erythrocytic
739 48hr-cycles following parasite delivery from the liver). neu: neutral, rec: recessive, dom:
740 dominant. Box-plots show the median and inter-quartile range (IQR), and the bottom and top
741 whiskers show the lowest data still within 1.5xIQR of the lower quartile and the highest data
742 still within 1.5xIQR of the upper quartile, respectively. Outlier values are shown as dots.

743

744 **Figure 3. Proportion of infections carrying mutant parasites.** Data are from 20,000
745 simulations, with one simulation representing one human infected host. **A:** y-axis scale ranges

746 from 0 to 100; **B**: same data as in **A** but y-axis scale ranges from 0 to 2.5. Black, red, and blue
747 lines represent infections after 5, 6, and 7 erythrocytic 48hr-cycles, respectively, following
748 parasite release from the liver. This corresponds to a mean of 1.2×10^{10} , 1.5×10^{11} , and 1.8×10^{12}
749 parasites per host, respectively. The mtDNA copy number is 20, the mutation rate is 10^{-10}
750 /nucleotide/replication, and the mutation cost is recessive in the simulations presented here.
751 $\geq 1/20$ refers to parasites having at least one of their 20 mtDNA copies being mutated (*id est*
752 all-mutant); $\geq 10/20$ refers to parasites having at least 10 of their 20 mtDNA copies being
753 mutated; and $20/20$ refers to parasites having all of their 20 mtDNA copies being mutated (*id*
754 *est* homoplasmic-mutant).
755
756

757 **Table 1. Patients reported in the study.**

Patient*	Sex	Age (year)	Weight (kg)	Isolate (day) [†]	Drug [‡]	Parasitemia (%)	Plasma drug (μM) ^{,**}				Parasite genetics ^{**}						
							Ato	Pro	Cyc	Others	<i>cytb</i>	<i>dhfr</i>	Microsatellites ^{§§}				
											TAA 81	TAA 87	PfPk2	Ara2	TAA 60		
P1	M	24	55	d0	AP	<0.005	-	-	-	-	Y	-	179	93	-	-	94
				d25/d0	AP	0.1	-	-	-	-	S	IRN	179	93	169	103	94
				d26/d1		-	1.20	0.48	0.18	neg	-	-	-	-	-	-	-
P2	M	12	40	d45/d20	QN	0.4	-	-	-	-	S	IRN	179	93	169	103	94
				d0	AP	2.9	neg	neg	neg	neg	Y	IRN	173	84	172	106	82
				d8		neg	-	-	-	-	-	-	-	-	-	-	-
P3	M	9	53	d35/d0	AP	0.5	neg	neg	neg	neg	S	IRN	173	84	172	106	82
				d65/d30	MFQ	<0.1	-	-	-	-	S	IRN	173	84	172	106	82
				d0	AP	6.6	neg	neg	neg	neg	Y	IRN	182	-	172	103	95
P4	F	59	64	d7		neg	4.12	0.02	neg	neg	Y	IRN	182	-	172	103	-
				d29/d0	AP	12.5	-	-	-	-	C	IRN	182	-	172	103	95
				d32/d3		0.01	-	-	-	-	C	-	-	-	172	103	95
P5	F	14	52	d49/d20	QN	3.5	0.39	neg	neg	neg	C	IRN	182	-	172	103	95
				d0	AP	1	-	-	-	-	-	-	-	-	-	-	-
				d12		neg	2.39	neg	neg	neg	Y	-	-	-	-	-	-
P6	M	0.5	8	d24/d0	AP	1	-	-	-	-	C	IRN	179	81	163	109	95
				d32/d8		neg	7.98	0.04	neg	neg	C	-	-	81	163	-	95
				d46/d22	QN	0.2	2.54	neg	neg	neg	C	IRN	179	81	163	109	94
P7	M	58	70	d0	AP	0.3	-	-	-	-	Y	IRN	179	84	169,172	103	79
				d10		neg	-	-	-	-	-	-	-	-	-	-	-
				d23/d0	AP	0.1	-	-	-	-	S	IRN	-	-	-	-	-
P6	M	0.5	8	d31/d8		<0.1 [§]	4.10	neg	neg	-	S	IRN	-	-	-	-	-
				d39/d16	MFQ	0.25	-	-	-	-	S	IRN	179	84	172	103	79
				d0	AP	4	-	-	-	-	-	-	-	-	-	-	-
P7	M	58	70	d3		<0.1	-	-	-	-	Y	IRN	179	96	190	112	91
				d19/d0	AP	6	-	-	-	-	Y+C	IRN	179	96	190	112	91
				d22/d3	MFQ	0.2	-	-	-	-	-	-	-	-	-	-	-
P7	M	58	70	d0	AP	2	neg	neg	neg	neg	Y	IRN	164	93	166	127	91
				d22		neg	-	-	-	-	-	-	-	-	-	-	-
				d27/d0	AP	1.5	0.10	neg	neg	neg	C+S [‡]	IRN	164	93	166	127	91
				d32/d5	QN	0.0003 [†]	3.62	0.09	0.04	neg	C+S	IRN	164	93	166	127	91

758 *, patients P1 to P7 were infected in The Union of the Comoros, Mali, Senegal, Gabon, Ivory Coast, The Union of the Comoros, and Togo,
759 respectively. All are of African ethnicity except P7 who is Caucasian; patient P5 was already reported in (11); additional informations and full
760 case report are provided here.

761 †, d0 corresponds to the day of diagnosis and treatment initiation.

762 ‡, drug used for treatment; AP, atovaquone-proguanil; MFQ, mefloquine; QN, quinine.
763 §, few trophozoites detected on the thin and thick smears.
764 ¶, calculated peripheral parasitemia, based on 14 parasites / μ L detected on the thick smear and a measured erythrocyte concentration of 3.7 T/L.
765 □, Ato, atovaquone; Pro, proguanil; Cyc, cycloguanil; Others: monodesethyl-chloroquine, chloroquine, doxycycline, sulfadoxine,
766 pyrimethamine, mefloquine, carboxy-mefloquine, amodiaquine, monodesethyl-amodiaquine, desbutyl-halofantrine, lumefantrine, dihydro-
767 artemisinin; the lower limit of quantification was 5 μ g/L, which corresponds to 0.014 μ M, 0.020 μ M, and 0.020 μ M, for atovaquone, cycloguanil
768 and proguanil, respectively.
769 **, "neg" means not detected ; "-" means not done.
770 ††, *cytb*: codon 268 was analyzed, wild type is Tyrosine (Y) and mutants are Serine (S) and Cysteine (C); the mutations *cytb* Y268S and Y268C
771 confer resistance to atovaquone; *dhfr*: the triple *dhfr* mutation N51I+C59R+S108N confers resistance to cycloguanil.
772 ‡‡, the presence of the 2 mutations Y268S and Y268C within the same isolate was confirmed by cloning the PCR product and subsequent
773 sequencing of multiple clones (supplementary figure 1).
774 §§, allele size (in base pair) of PCR products are reported.
775

776 **Table 2.** Time required to clear the *de novo* mtDNA mutant parasites emerging from primary
 777 infections.
 778

Total parasite load per patient	Fraction of mutated mtDNA copies [‡]	Mutant parasite load per patient*			Mutant clearance time (days) [†]
		Median	Min.	Max.	
1.8x10 ¹²	20/20	6	0	176,395	6.2
	≥10/20	651	99	1,480,258	7.2
	≥1/20	11,132	8,418	3,049,318	7.6
1.5x10 ¹¹	20/20	0	0	6,157	4.5
	≥10/20	25	0	79,843	5.8
	≥1/20	825	443	210,890	6.2
1.2x10 ¹⁰	20/20	0	0	448	3.1
	≥10/20	0	0	6,960	4.5
	≥1/20	58	17	18,352	5.0

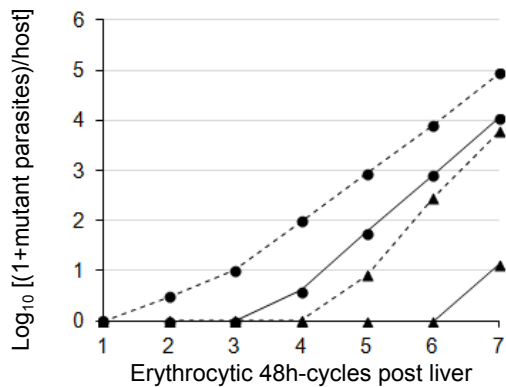
779 [‡], ≥1/20 refers to parasites having at least one of their 20 mtDNA copies being mutated (*id est* all-mutant);
 780

781 ≥10/20 refers to parasites having at least 10 of their 20 mtDNA copies being mutated; and 20/20 refers to
 782 parasites having all of their 20 mtDNA copies being mutated (*id est* homoplasmic-mutant)

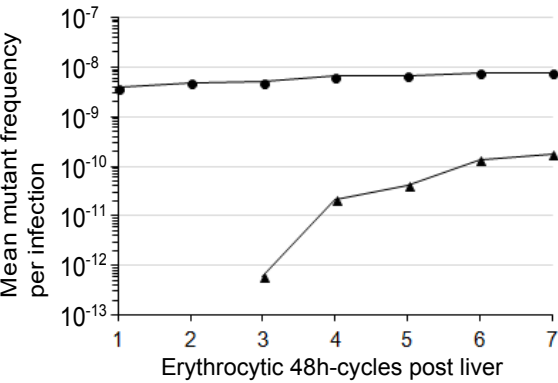
783 *, Data are from 20,000 simulations performed with the following parameters: recessive mutation cost, mtDNA
 784 copy number = 20, and mutation rate = 10⁻¹⁰/nucleotidic site/replication.

785 [†], Assuming a constant parasite reduction ratio for AP-resistant parasites of 50. Maximum (Max.) mutant
 786 parasite loads are used for the estimation.

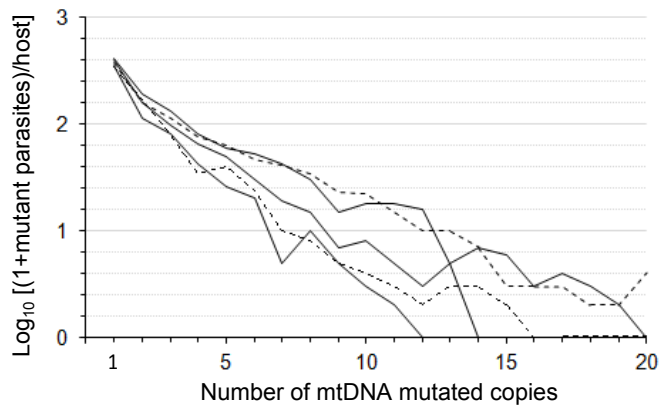
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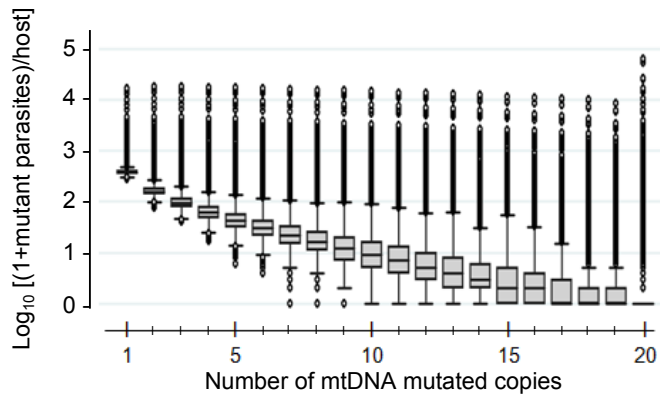
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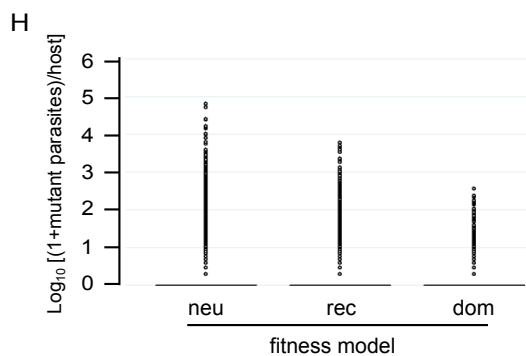
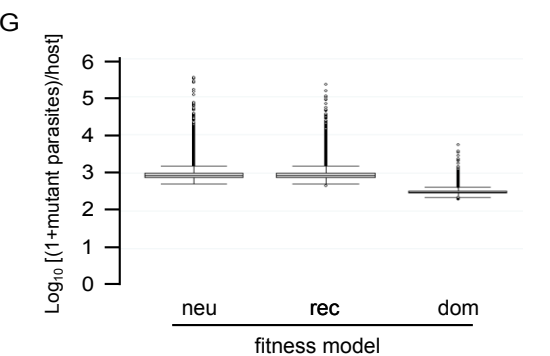
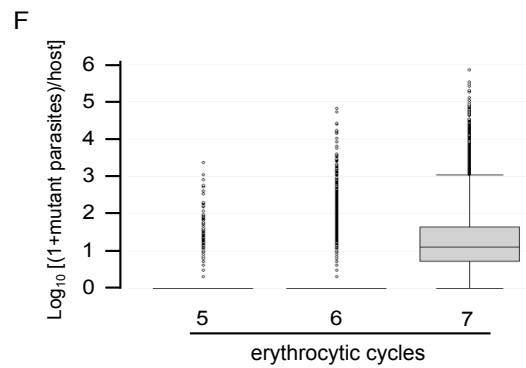
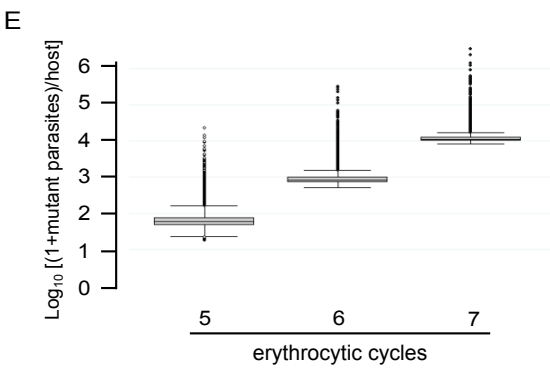
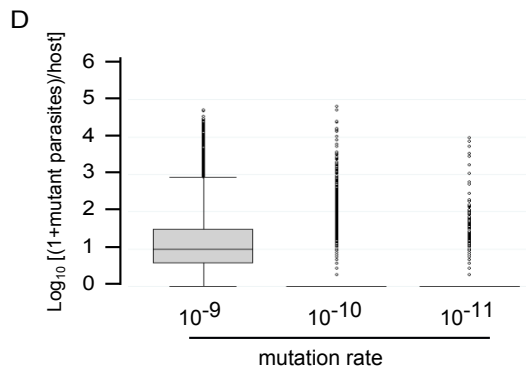
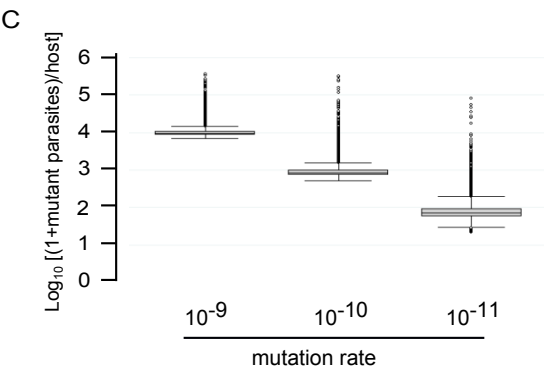
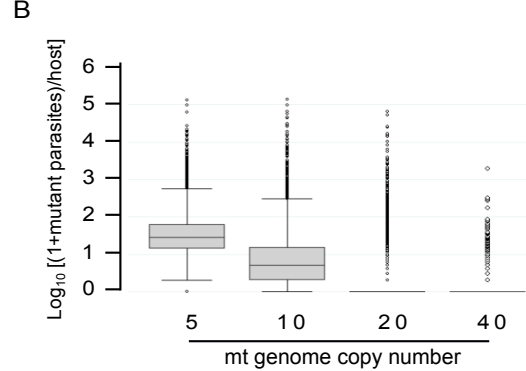
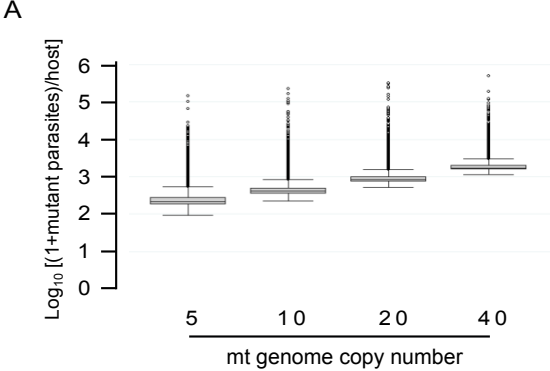


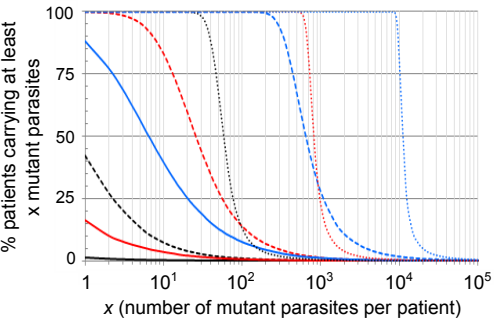
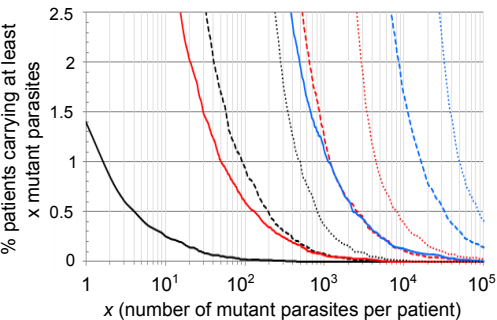
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D





A**B**

Supplementary materials

1) The mathematical description of the model:

The following sections describe the appearance of mtDNA mutations and their propagation to daughter mtDNA copies and parasites along one erythrocytic 48hr-cycle. This erythrocytic 48hr-cycle was repeated up to 7 times in a row to simulate the parasite blood stage growth during a *P. falciparum* malaria primary infection in a non-immune patient. During one intra-erythrocytic 48h-cycle, each *P. falciparum* parasite undergoes 5 consecutive endo-mitosis (that occur within a single parasite), resulting theoretically in the production of $2^5 = 32$ daughter parasites per initial parasite.

Spontaneous mutation

At the mtDNA replication d , each wild type parasite has a probability of spontaneous mtDNA mutation $p = 1 - (1 - \mu)^n$, where μ is the mutation rate and n is the mtDNA copy number.

The probability of 2 or more spontaneous mutations in the same parasite as well as the probability of a spontaneous mutation among the parasite populations $P_{1,d}, \dots, P_{n,d}$ were assumed to be negligible (where $P_{i,d}$ is the population of mutant parasites having i mtDNA copies being mutated).

At each mtDNA replication d , the number of wild type parasites which mutate spontaneously has a binomial distribution $\text{Bin}(N_{0,d}, p)$, where $N_{0,d}$ is the number of wild type parasite at the division d .

Duplication of the mtDNA

The n mtDNA template copies to be duplicated during one mtDNA replication are randomly drawn with replacement among the n initial mtDNA copies. Thus, for a parasite with k mutated mtDNA copies (k in $\{0, \dots, n\}$), the number M of mutated mtDNA copies that are duplicated during one division has a binomial distribution $\text{Bin}(n, k/n)$, with the corresponding probability $p_{\text{repl}_i} = P(M=i)$.

The $N_{k,d}$ parasites with k mtDNA mutated copies at replication d generate potentially (at most) $n+1$ distinct mutant parasite populations having a duplicated mtDNA genome: the population $P_{k,d,0}$ for which 0 mutated mtDNA copy have been duplicated, the population $P_{k,d,1}$ for which 1 mutated mtDNA copy have been duplicated..., the population $P_{k,d,n}$ for which n mutated mtDNA copies have been duplicated.

All the parasites of a population $P_{k,d,x}$ have $k+x$ mutated mtDNA copies among $2n$ (x in $\{0, \dots, n\}$).

$(N_{k,d,0}, N_{k,d,1}, \dots, N_{k,d,n})$ has a multinomial distribution $M(N_{k,d}, p_{\text{repl}_0}, p_{\text{repl}_1}, \dots, p_{\text{repl}_n})$, where $N_{k,d,x}$ is

the size of a parasite population $P_{k,d,x}$ and $\sum_{x=0}^n N_{k,d,x} = N_{k,d}$

Partitioning of the mtDNA copies among 2 daughter separated mitochondrial units

The mtDNA duplication for all parasite populations $P_{1,d}, \dots, P_{n,d}$ at the replication d generates potentially $2n+1$ parasite populations $P'_{k,d}$ (k in $\{0, \dots, 2n\}$), where k is the number of mutated mtDNA copies among $2n$. The segregation of n mtDNA copies is modelled as the random draw without replacement of n mtDNA copies among $2n$, generating 2 separated daughter mtDNA unit

having each n mtDNA copies. The daughter mtDNA units being separated, they were further considered as independent daughter “transient” parasites for convenience.

First case: $k < n$

Each parasite of a population $P'_{k,d}$ generates one of the $k+1$ different couples C^1_j of daughter parasites (j in $\{0, \dots, k\}$), with a probability $P_{C^1_j}$ according to an hypergeometric distribution $H(2n, k, n)$. A couple C^1_j contains a daughter parasite with j mutated mtDNA copies among n and the other with $k-j$ mutated mtDNA copies among n .

The $N'_{k,d}$ parasites of the population $P'_{k,d}$ generate $N'_{k,d,j}$ couples C^1_j , and $\sum_{j=0}^k N'_{k,d,j} = N'_{k,d}$
 $(N'_{k,d,0}, N'_{k,d,1}, \dots, N'_{k,d,k})$ has a multinomial distribution $M(N'_{k,d}, P_{C^1_0}, P_{C^1_1}, \dots, P_{C^1_k})$.

Second case: $k \geq n$

Each parasite of a population $P'_{k,d}$ generates one of the $k+1$ different couples C^2_j of daughter parasites (j in $\{0, \dots, k\}$), with a probability $P_{C^2_j}$ according to an hypergeometric distribution $H(2n, k, n)$. A couple C^2_j contains one daughter parasite with j wild type mtDNA copies among n and the other with $k-j$ wild type mtDNA copies among n .

The $N'_{k,d}$ parasites of the population $P'_{k,d}$ generate $N'_{k,d,j}$ couples C^2_j and $\sum_{j=0}^k N'_{k,d,j} = N'_{k,d}$
 $(N'_{k,d,0}, N'_{k,d,1}, \dots, N'_{k,d,k})$ has a multinomial distribution $M(N'_{k,d}, P_{C^2_0}, P_{C^2_1}, \dots, P_{C^2_k})$

After 5 consecutive cycles of this duplication-partitioning process (which mimic the 5 consecutive endo-mitosis that occur within a single parasite during its erythrocytic 48h-cycle), the number of survival parasites from each genotypically distinct parasite population (wild-type, heteroplasmic, homoplasmic-mutant) is drawn in a binomial distribution $\text{Bin}(N_i, p_{\text{surv}})$, where N_i is the number of parasite of the parasite population with i mutated copies (from 0 to n) and p_{surv} is the survival probability of each parasite population (varying according to the number of mutated mtDNA copies per parasite, as explained in the main section). Each surviving parasite will initiate a new erythrocytic 48hr-cycle.

2) Supplementary results & discussion

Case reports:

Patient 1 is a 24-year-old African male (weight: 55 kg) living in La Réunion Island, France. He visited family during three months in an urban area in The Union of the Comoros in 2008-09. He declared not taking any antimalarial chemoprophylaxis. Thirteen days after returning home he started experiencing fever and vomiting. A peripheral blood film examination performed at the hospital

laboratory showed *P. falciparum* (parasitemia: <0.005%). A standard 3-day AP treatment (1,000 mg of atovaquone and 400 mg of proguanil, once a day for 3 days) was prescribed but was incompletely taken: the patient received the first dose of AP at the hospital and went home. He took the second dose at home while vomiting, and did not take the third dose because he felt better. At day-25 the patient presented to the hospital and blood smears showed *P. falciparum* parasites (parasitemia: 0.1%). The patient was admitted to hospital for 4 days, and with the history of vomiting during the treatment of the first malaria episode, the recrudescence infection was treated again with a standard 3-day AP treatment. No vomiting was reported during this treatment period. At day-45 (day-20 after the treatment of the recrudescence infection) the patient presented to the hospital with fever (symptoms have started 4 days earlier) and blood smears showed *P. falciparum* parasites (parasitemia: 0.4%). He was admitted to the hospital (4-day stay) and the second recrudescence infection was successfully treated with quinine for seven days. Parasite DNA was extracted from day-0, day-25, day-26 and day-45 isolates (either directly from blood samples or from blood smears or plasma).

Patient 2 is a 12-year-old male weighing 40 kg. He was born in France to African parents living in France. He travelled during 5 weeks to Mali during summer 2010. He declared using chloroquine as antimalarial chemoprophylaxis but stopped prematurely. Eight days after returning to France he started experiencing fever without vomiting. A peripheral blood film examination showed *P. falciparum* parasites (parasitemia: 2.9%). The patient was admitted to the hospital for 2 days and treated with 750 mg of atovaquone and 300 mg of proguanil, once a day for 3 days. Vomiting occurred 1h20min after intake of the first dose. At the day-8 follow-up, no parasites were detected. At day-35, the patient presented to the hospital with fever that started 4 days earlier, headache and body aches ; *P. falciparum* trophozoites were detected on blood film (parasitemia: 0.5%). The patient was treated with 1,000 mg of atovaquone and 400 mg of proguanil, once a day for 5 days instead of 3 days. The patient was not admitted to hospital and the treatment was not supervised. At day-65 (day-30 after the treatment of the recrudescence infection), the patient had fever and trophozoites and gametocytes were detected (parasitemia: <0.1%). The second recrudescence infection was successfully treated with oral mefloquine. Parasite DNA was extracted from day-0, day-35, and day-65 isolates (directly from blood samples).

Patient 3 is a 9-year-old African boy (weight: 53 kg) living in France who travelled during two months to Senegal in summer 2011 without antimalarial chemoprophylaxis. Two weeks after returning to France he started experiencing fever and vomiting. A peripheral blood film examination performed at the medical care unit showed *P. falciparum* (parasitemia: 6.6%). The patient was admitted to the hospital (4-day stay) and treated with 1,000 mg of atovaquone and 400 mg of proguanil, once a day for 3 days. Drug intakes (crushed tablets during the meal together with milk and plain yoghurt) were supervised. Vomiting has been reported during hospitalization. Blood film examination at day-3 post-treatment showed parasites (parasitemia: 1.2%). At the day-7 follow-up, both blood film and thick smear showed gametocytes only. At day-29 the patient presented to the hospital with fever and blood

smears showed *P. falciparum* parasites (parasitemia: 12.5%). He was admitted to the hospital (4-day stay) and as vomiting had been reported following the initial treatment he was prescribed another 3-day full course of AP. Drug intakes (crushed tablets during the meal together with milk and plain yoghurt) were supervised. During the 3-day treatment schedule, the course of the treatment was altered because of vomiting events: the patient received 5 doses instead of 3 doses of 1,000 mg of atovaquone and 400 mg of proguanil because two of them were followed by vomiting. At day-32 (day-3 follow-up after the treatment of the recrudescent infection), blood film showed trophozoites (parasitemia: 0.01%). At day-49 (day-20 after the treatment of the recrudescent infection), the patient had fever and trophozoites were detected (parasitemia: 3.5%). He was admitted to the hospital and the recrudescent infection was successfully treated with oral quinine for seven days. Parasite DNA was extracted from day-0, day-7, day-24, day-29, day-32 and day-49 isolates (either directly from blood samples or from blood smears).

Patient 4 is a 59-year-old female weighing 64 kg. She is of African origin (native from Gabon). She is living in France since 25 years and visits Gabon every year. She travelled during 3 weeks to urban an area in Gabon during January/February 2012 without taking antimalarial prophylaxis. Twelve days after returning to France, she experienced a malaria episode with *Plasmodium* parasites evidenced on blood film examination (parasitemia: 1%) and she was treated with a full course of AP (no diet at the first dose). At day-12, no parasites were detected neither using microscopic examination nor PCR typing of peripheral blood. At day-24, the patient presented at the hospital and trophozoites were detected (parasitemia: 1%). The patient was treated again with 1,000 mg of atovaquone and 400 mg of proguanil, once a day for 3 days. At day-32 (day-8 after the treatment of the recrudescent infection), blood film and thick smear were performed and no replicating parasites were detected but gametocytes were observed. At day-46 (day-22 after the treatment of the recrudescent infection), trophozoites were detected (parasitemia: 0.2%). The second recrudescent infection was successfully treated with oral quinine for seven days. Parasite DNA was extracted from day-12, day-24, day-32 and day-46 isolates (directly from blood samples).

Patient 5 is a 14-year-old African girl (weight: 52 kg) living in France, who travelled during one month to Ivory Coast in 2005. She declared using chloroquine as antimalarial chemoprophylaxis. Three days after returning to France she started experiencing fever with abdominal, articular and cervical pain, but without vomiting nor diarrhoea nor obtundation. A peripheral blood film examination showed *P. falciparum* parasites (parasitemia: 0.3%). The patient was admitted to the hospital for 3 days and was treated with 1,000 mg of atovaquone and 400 mg of proguanil, once a day for 3 days. The treatment however was not supervised and was later reported to be incompletely taken because of vomiting coincidentally with 2 of the 3 doses. At the day-10 follow-up, no parasites were detected using microscopic examination of peripheral blood (thin & thick). At day-23 the patient presented to the hospital with fever and vomiting which started 4 days earlier, and headaches. Blood smears showed *P. falciparum* parasites (parasitemia: 0.1%). An acute primary infection caused by

hepatitis A virus was also diagnosed concomitantly. The patient was admitted to the hospital for 4 days. With the history of vomiting during the treatment of the first malaria episode, the recrudescence infection was treated again with a standard 3-day AP treatment. Drug intakes (together with fatty food: milk and plain yoghurt) were supervised and no vomiting were observed. Symptoms disappeared during treatment. At day-31 (day-8 after the treatment of the recrudescence infection), examination of peripheral blood showed many gametocytes and few trophozoites on the thin and thick smear (parasitemia: <0.1%). The family of the patient was contacted. The patient presented to hospital on day-39: she was asymptomatic but trophozoites were detected on blood film (parasitemia: 0.25%). The patient was admitted to the hospital for 3 days and the second recrudescence infection was successfully treated with oral mefloquine (no parasites detected at days 2, 10 and 28 following mefloquine). Parasite DNA was extracted from day-0, day-23 day-31, and day-39 isolates (either directly from blood samples or from blood smears).

Patient 6 is a 5-month-old African boy (weight: 8 kg) living in France, who travelled during two weeks to the Union of the Comoros in 2008 without taking antimalarial prophylaxis. One day after returning to France the family took him to the hospital because of fever, diarrhoea and vomiting which started three days prior. A peripheral blood film examination showed *P. falciparum* parasites (parasitemia: 4%). The patient was admitted to the hospital for 3 days and was treated with 125 mg of atovaquone and 50 mg of proguanil, once a day for 3 days. The treatment was supervised. At the day-3 follow-up, few trophozoites were detected using microscopic examination of peripheral blood (parasitemia <0.1%). At day-19 his mother took him to the hospital because of diarrhoea and fever which started on the same morning. Blood smears showed *P. falciparum* parasites (parasitemia: 6%). The patient was admitted to the hospital for 3 days and was treated with 125 mg of atovaquone and 50 mg of proguanil, once a day for 3 days. Drug intakes (crushed tablets during the meal together with milk and plain yoghurt) were supervised. At day-22 (day-3 after the treatment of the recrudescence infection), trophozoites were detected using microscopic examination of peripheral blood (parasitemia: 0.2%). A treatment with mefloquine was started, and day-26 follow-up showed gametocytes only. Parasite DNA was extracted from day-3 and day-19 isolates (directly from blood samples).

Patient 7 is a 58-year-old male (weight: 70 kg) living in France, who experienced several *P. falciparum* malaria episodes during the last nineteen years. In 2010 he travelled during four days to Togo without taking antimalarial prophylaxis. Seven days after returning home he went to the hospital because of fever and chills without vomiting. A peripheral blood film examination performed at the hospital laboratory showed *P. falciparum* parasites (parasitemia: 2%). A standard 3-day treatment of AP was prescribed and the patient went home. At day-27 the patient presented to the hospital because of with fever and vomiting since 48 hours. Blood smears showed *P. falciparum* parasites (parasitemia: 1.5%). A standard 3-day treatment of AP was prescribed and the patient went home. At day-32 (day-5 after the treatment of the recrudescence infection), few trophozoites were detected using microscopic examination of peripheral blood (calculated parasitemia of 0.0003%, based on 13 parasites / μ L

detected on the thick smear and a measured erythrocyte concentration of 3.7 Tera/L). The patient was successfully treated with quinine during 7 days (no trophozoites detected at days 5, 13 and 28 following quinine). Parasite DNA was extracted from day-0, day-27, and day-32 isolates directly from blood samples.

We are not aware of any other AP-resistant infections, as evidenced by molecular analysis and treatment history, which have been treated with AP. However, the pattern of recrudescence following two consecutive AP treatments reported in one patient by Kuhn et al. (2005) strikingly resembles the pattern of our 7 cases reports. Unfortunately, some key genetics data were not available for this case, precluding further interpretation regarding how AP-resistant infections respond to AP. Surprisingly, we observed that a significant fraction of AP-resistant parasites were killed by AP during the first days of treatment, leading to a late treatment failure. This is a striking example as the *cytb*²⁶⁸ mutation is the canonical single-step mutation that confers high-grade resistance to an antimalarial drug (atovaquone).

These observations could be explained by several factors, as suggested in the main discussion section. In addition, confounding factors could also have contributed to the decrease in parasitemia: 1) developing acquired immunity (not consistent with the sharp decrease observed concomitantly to treatment administration, and not consistent with similar time to recrudescence and parasitemia for the first and second failure) ; 2) concurrent intake of other compounds having antimalarial activity ; for 3 of the patients for whom relevant plasma were available (patients P1, P4 and P7), the drug dosage did not detect any additional standard antimalarial ; 3) residual drug concentrations from the first AP treatment might have resulted in higher drug concentrations when starting the second AP treatment; when available, drug dosages did not show any unusually high plasma drug concentrations.

We estimated the PRR for AP-resistant parasites to be ~50 using microscopy-derived parasite counts from 3 patients. However, caution should be taken regarding the PRR estimate we provide because 1) one patient (P3) received an altered course of AP (5 doses instead of 3 during the 3-day course of the treatment because two of them were followed by vomiting) and we cannot exclude that drug concentrations attained unusually high values, and 2) only two values of parasitemias and including day-0 (at day-0 and day-3 for patients P3 and P6, and at day-0 and day-5 for patient P7) were used to estimate the PRR and we cannot assess whether these points were in the linear portion of the parasite clearance curve nor could we take into account the lag phase (Flegg 2011, Nkhoma 2013).

On the origin of the mtDNA mutations conferring atovaquone resistance

1. On the atovaquone-induced mtDNA mutation hypothesis

A popular hypothesis suggests that atovaquone could have a local mitochondrial mutagenic activity through the accumulation of electrons and superoxide, as a consequence of atovaquone blocking the mitochondrial electron transport chain (Srivastava 1999). This could theoretically result in increased

frequency of resistance acquisition. One major drawback with this hypothesis is that more than one mutated copy per parasite would have to be induced, since one mutated copy per parasite is unlikely to confer high-grade atovaquone resistance. Even when considering a massive and transient burst in mtDNA mutation rate, it is very unlikely that several copies of the same parasite will be mutated simultaneously at the *cytb*²⁶⁸ codon. Then, propagation of the atovaquone-induced mutation to daughter copies and parasites would require extensive mtDNA replication and cell division which is unlikely to occur during treatment because the high drug concentrations will likely arrest the growth of (and probably destroy) parasites carrying one or few mutated mtDNA copies. Our simulations show that asexual clonal expansion of parasites during the erythrocytic growth phase generates enough mtDNA mutations to repeatedly produce mtDNA mutant parasites before treatment initiation. In conclusion, we did not test directly the possibility of atovaquone-induced mutations. However we speculate that, if it occurred, atovaquone-induced mutagenesis would contribute marginally to the pool of mtDNA-mutated parasites produced before drug selection.

2. On additional notable findings

First, in one patient (P7) the presence of the 2 different mutations *cytb*^{Y268S} and *cytb*^{Y268C} within the day-of-failure isolates was detected (which was confirmed by cloning and sequencing of the PCR product; supplementary figure 1). This shows that at least two different mutational events occurred at the *cytb*²⁶⁸ codon within the same host. These data confirm that mtDNA mutations can be repeatedly produced within short-term single-host infections, which is consistent with our simulations.

Second, in patient P6 the presence of the wild type genotype (*cytb*^{Y268}) was detected in addition to the mutant *cytb*^{Y268C} within the day-of-failure isolate. We have not yet further explored the genotypic description of this complex genotype. We predict that the presence of the wild type allele is contributed by heteroplasmic parasites (having some but not all of their mtDNA copies not mutated) rather than by wild type parasites that would have survived to AP treatment. Experiments have been designed to check this prediction.

Table S1. Distribution of mutant parasites and mutant alleles within infections.

	Mean	Median	Percentiles				
			5th	25th	75th	95th	99th
Recessive, 20 cop, 4 cycles							
Total parasite load	1.04x10 ⁹	1.04x10 ⁹					
≥1/20-mutant load	6	3	0	2	6	16	46
≥10/20-mutant load	0	0	0	0	0	0	4
20/20-mutant load	0	0	0	0	0	0	0
Mutation freq (x 10 ⁻¹⁰)	9.1	2.4	0	1.0	5.3	24	100
Recessive, 20 cop, 5 cycles							
Total parasite load	1.24x10 ¹⁰	1.24x10 ¹⁰					
≥1/20-mutant load	83	58	34	46	77	156	499
≥10/20-mutant load	7	0	0	0	2	15	92
20/20-mutant load	0	0	0	0	0	0	1
Mutation freq (x 10 ⁻¹⁰)	11.8	5.1	2.2	3.5	8.2	5.7	109
Recessive, 20 cop, 6 cycles							
Total parasite load	1.49x10 ¹¹	1.49x10 ¹¹					
≥1/20-mutant load	1,086	825	638	731	984	1,762	4,467
≥10/20-mutant load	117	25	5	13	55	275	1,183
20/20-mutant load	5	0	0	0	0	5	50
Mutation freq (x 10 ⁻¹⁰)	14.4	7.5	4.6	5.9	10.6	28.7	98
Recessive, 20 cop, 7 cycles							
Total parasite load	1.79x10 ¹²	1.79x10 ¹²					
≥1/20-mutant load	13,820	11,132	9,497	10,287	12,629	20,080	49,580
≥10/20-mutant load	1,786	651	287	447	1,089	3,778	16,038
20/20-mutant load	102	6	0	2	20	168	1,150
Mutation freq (x 10 ⁻¹⁰)	16.7	9.9	7.1	8.4	12.3	29.5	101

Data are from 20,000 simulations performed with the following parameters: recessive mutation cost, mtDNA copy number = 20, and mutation rate = 10⁻¹⁰/nucleotidic site/replication. ≥1/20 refers to parasites having at least one of their 20 mtDNA copies being mutated (*id est* all-mutant); ≥10/20 refers to parasites having at least 10 of their 20 mtDNA copies being mutated; and 20/20 refers to parasites having all of their 20 mtDNA copies being mutated (*id est* homoplasmic-mutant). The mutation frequency (freq) was calculated as the number of parasite mtDNA mutant copies per host divided by the total number of parasite mtDNA copies per host.

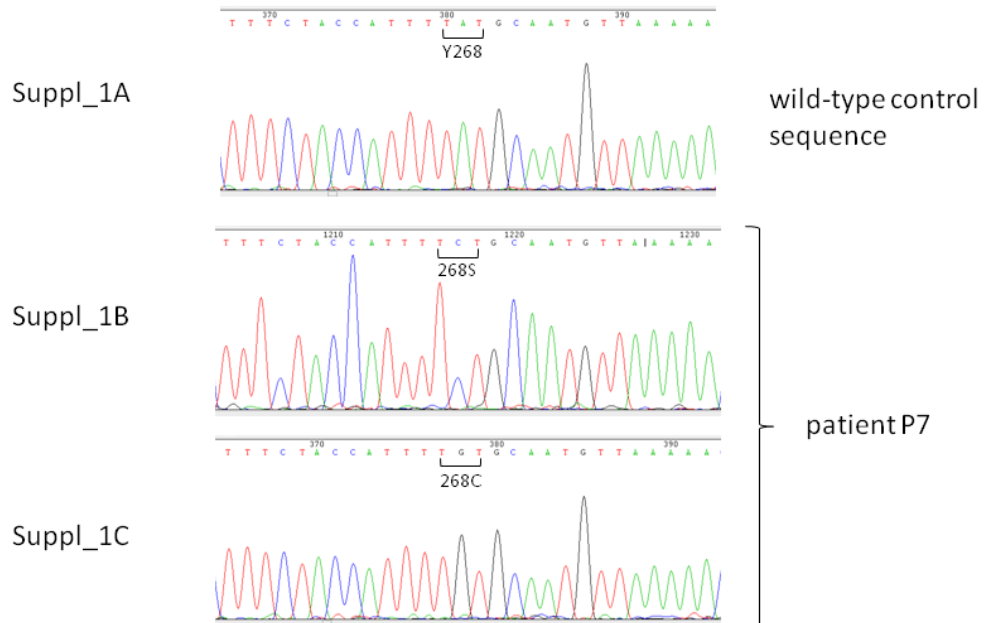
Table S2. Data on 26 published cases of failure of atovaquone-proguanil treatment for *P. falciparum* malaria associated with the *cytb*²⁶⁸ mutation.

Age (year)	Country of infection	Parasitemia (%)			<i>cytb</i> ²⁶⁸ ,§		<i>dhfr</i> ^{*,§}	Ref
		d0	d _{fail}	d _{fail}	d0	d _{fail}	d _{fail}	
38	Burkina Faso	0.35	0.47	22	Y	C	3M	Musset 2006
51	Burkina Faso	nd	0.04	25	nd	S	3M	Musset 2006
36	Guinea	13	5	26	Y	S	3M	Musset 2006
55	Ivory Coast	4	5	26	Y	C	3M	Musset 2006
23	Burkina Faso/Senegal	2.8	1.5	28	Y	S	3M	Musset 2006
18	Comoros	0.5	1.3	23	Y	S	3M	Savini 2008
nd	French Guiana	nd	1	49	Y	S	3M	Legrand 2007
3.5	Mozambique	1.2	3.2	28	nd	S	nd	Rose 2008
21	India	3.4	2	34	nd	C	nd	Perry 2009
29	Sierra Leone	1.1	nd	42	nd	C	nd	Sutherland 2008
5	Nigeria	0.1	0.3	25	nd	S	nd	Sutherland 2008
30	Uganda	nd	0.2	21	nd	C	nd	Sutherland 2008
36	Uganda/Kenya	0.1	<0.1	26	Y	C	nd	Sutherland 2008
47	The Gambia	nd	3	32	nd	C	nd	Sutherland 2008
28	Cameroon	1	2.5	21	nd	S	nd	David 2003
24	Kenya	3	nd	30	Y	S	mut	Schwartz 2003
25	Sierra Leone	nd	nd	19	Y	S	2M	Kuhn 2005
45	Nigeria	1.5	<1	28	nd	N	nd	Fivelman 2002
28	Mali	nd	1.5	28	nd	S	nd	Winchmann 2004
24	Comoros	0.005	0.1	25	Y	S	3M	Current study
12	Mali	2.9	0.5	35	Y	S	3M	Current study
9	Senegal	6.6	12.5	29	Y	C	3M	Current study
59	Gabon	1	1	24	Y	C	3M	Current study
14	Ivory Coast	0.3	0.1	39	Y	S	3M	Current study
0.5	Comoros	4	6	19	Y	Y+C	3M	Current study
58	Togo	2	1.5	27	Y	C+S	3M	Current study

*, d0 and d_{fail} refer to day of diagnosis and day of failure, respectively;

§, The mutations *cytb* Y268S and Y268C confer resistance to atovaquone; 2M and 3M refer to double and the triple *dhfr* mutations, respectively, that confer resistance to cycloguanil.

Supplementary figure 1. Presence of the 2 *cytb* mutations Y268S and Y268C within the day-22 isolate from patient P7. Sequences shown in Suppl_1B and suppl_1C were obtained from different clones of the same PCR product.



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