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1 **Superoxide: A major role in the mechanism of action of essential antimalarial** 2 **drugs**

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17 **Abstract**

18 Understanding the mode of action of antimalarials is central to optimizing their use and the discovery
19 of new therapeutics. Currently used antimalarials belong to a limited series of chemical structures
20 and their mechanisms of action are continually debated. Whereas the involvement of reactive
21 species that in turn kill the parasites sensitive to oxidative stress, is accepted for artemisinins, little is
22 known about the generation of such species in the case of quinolines or hydroxynaphtoquinone.
23 Moreover, the nature of the reactive species involved has never been characterized in *Plasmodium*-
24 infected erythrocytes. The aim of this work was to determine and elucidate the production of the
25 primary radical, superoxide in *Plasmodium*-infected erythrocytes treated with artemisinin,
26 dihydroartemisinin, chloroquine and atovaquone, as representatives of three major classes of
27 antimalarial. The intracellular generation of superoxide was quantified by liquid chromatography
28 coupled to mass spectrometry (LC-MS). We demonstrated that artemisinins, atovaquone and to a
29 lesser extent chloroquine, generate significant levels of superoxide radicals in *Plasmodium*
30 *falciparum* sensitive strains. More so, the production of superoxide was lowered in chloroquine-
31 resistant strain of *Plasmodium* treated with chloroquine. These results consolidate the knowledge
32 about the mechanism of action of these different antimalarials and should be taken into
33 consideration in the design of future drugs to fight drug-resistant parasites.

34 **Keywords:** *Plasmodium falciparum*, antimalarials, superoxide radicals, mechanism of action, LC-MS.

38 **Introduction**

39 Malaria is one of the most killer-diseases in the world [1], for which several drugs are in use.
40 Artemisinins (representative of endoperoxide drugs), quinolines, and hydroxynaphtoquinones are
41 the three major classes of antimalarials, but their mechanisms of action are still debated. Indeed, the
42 activation of artemisinins is thought to involve iron-catalyzed reductive homolytic cleavage of the
43 endoperoxide bridge, generating carbon-centered radicals, an alkylating agent that reacts with
44 essential biomolecules [2,3]. Hence, the carbon-centered radical formed can alkylate heme produced
45 during the hemoglobin digestion [4,5], preventing its polymerization into hemozoin, leading to the
46 accumulation of toxic redox-active iron complexes [6–9].

47 Several mechanisms of action have been proposed for chloroquine (representative of quinoline
48 drugs): interaction with heme, blocking its detoxification into hemozoin [10], interaction with the
49 DNA of *Plasmodium* [11], modulation of immune response [12] and/or inhibition of peroxidative
50 degradation of heme [13].

51 The mechanism of action of atovaquone (representative of hydroxynaphtoquinone drugs) is quite
52 different and related to the blocking of the mitochondrial electron transport chain at complex III of
53 the respiratory chain of *Plasmodium*, which leads to parasite death [14]. Atovaquone is a competitive
54 inhibitor of ubiquinol binding, which specifically inhibits the complex III (cytochrome bc1) of the
55 electron transport chain of the parasite, leading to the loss of the membrane potential and
56 consequently to the parasite death [15,16].

57 While the probable production of reactive species has been largely accepted and discussed in
58 literature for artemisinins (ARTs) [8,17], the specific detection of such radical species has never been
59 investigated up till date in *Plasmodium*-infected red blood cells (RBCs), even though the production
60 of hydroxyl radicals by reaction of artemisinin with cancer cells (rich in iron) has been described [18].
61 Most of the measurements have been carried out using nonspecific fluorescence probes such as
62 CellRox or dichlorofluorescein (DCF) derivatives [6,8,9,19,20], but the nature of the primary radicals
63 has never been determined in *Plasmodium*, for any of the antimalarial drugs mentioned above.
64 Identifying the precise nature of the generated radicals will be useful to understand the mechanism
65 of action of these drugs, and also the parasite resistance mechanisms, and could serve as a guide in
66 the design and development of future antimalarials.

67 The aim of the present work is to investigate the involvement of reactive species in the mode of
68 action of antiplasmodial drugs by killing parasites sensitive to oxidative stress, and to determine for
69 the first time, the nature of such radicals using a very sensitive technique by LC-MS that we recently
70 developed [21].

71

72 **Materials and Methods**

73 **Materials**

74 Unless otherwise stated, all reagents and the molecules tested (artemisinin (ART), atovaquone (ATQ)
75 and chloroquine (CQ)) were supplied by Sigma Aldrich. Dihydroartemisinin (DHA) was synthesized by
76 chemists from our laboratory. Stock solutions were prepared in DMSO except for CQ (in RPMI or
77 PBS). The final concentration of each molecule was between 0.5-500 nM while the DMSO control was
78 0.2 % which was similar to that contained in the solutions of the molecules of interest.

79 **Methods**

80 **Interaction of antimalarials with iron (II) by electron paramagnetic resonance**

81 Electron paramagnetic resonance (EPR) measurements were carried out using 5,5-dimethyl-1-
82 pyrroline *N*-oxide (DMPO) as spin trap (stock solution 1 M in water). The analyses were performed on
83 mixtures containing DMPO (100 mM), the molecule of interest (9 mM in DMSO or PBS) and a Fe(II)
84 salt (Mohr's salt) (2 mM). The resulting solution was taken into an EPR flat quartz cell and the spectra
85 immediately recorded. The amount of radicals was calculated from the double integration of the
86 spectra.

87 EPR spectra were obtained at room temperature using the X-band on a Bruker EMX-8/2.7 (9.86 GHz)
88 equipped with a gaussmeter (Bruker, Wissembourg, France) and a high-sensitivity cavity (4119/HS
89 0205). Analyses were performed using a flat quartz cell (FZKI160-5 X 0.3 mm, Magnostech, Berlin,
90 Germany). WINEPR and SIMFONIA software (Bruker, Wissembourg, France) were used for EPR data
91 processing. Typical scanning parameters were: scan number, 6; scan rate, 1.2 G/s; modulation
92 frequency, 100 kHz; modulation amplitude, 1 G; microwave power, 20 mW; sweep width, 100 G;
93 sweep time, 83.88 s; time constant, 40.96 ms; magnetic field 3460-3560 G.

94 **Parasite culture and samples preparation**

95 The FcB1-Colombia (a chloroquine-resistant strain) and F32-Tanzania (a chloroquine-sensitive strain)
96 were used at the trophozoite stage (24-36 h post-invasion). The parasites were maintained in RPMI
97 at 5 % human serum and 2 % hematocrit. Parasites were firstly synchronized at the ring stage with 5
98 % D-sorbitol solution [22]. Non-concentrated (5 % parasitemia) and concentrated cultures (>70 %
99 parasitemia) were used respectively for the investigation. Indeed, to ensure that superoxide radicals
100 detected are emanating exclusively from the parasites and not from oxidized red blood cells, the
101 same analysis was conducted both on non-concentrated and concentrated *Plasmodium* cultures. To
102 concentrate the parasite-infected erythrocytes, the parasite culture was passed through a magnetic
103 column where the infected erythrocytes were trapped due to their high hemozoin content, allowing
104 the uninfected ones to be eluted [23]. The use of the FcB1-Colombia *versus* F32-Tanzania was aimed
105 at comparing the superoxide generating effect of chloroquine on both chloroquine-resistant and
106 chloroquine-sensitive strains, respectively.

107 **ROS quantification by LC-MS**

108 The production of superoxide radicals ($O_2^{\cdot-}$) after the treatment of *Plasmodium*-infected erythrocytes
109 was monitored using the liquid chromatography coupled to mass spectrometry (LC-MS) [21] using
110 dihydroethidium (DHE) as the probe. Precisely 681 μ L of the sample (parasitized RBCs culture) at a
111 concentration of 15 million cells/mL in phosphate buffer saline (PBS) was introduced into a 1.5 mL
112 tube and immediately probed with DHE at 10 μ M final concentration. Each tube was treated with
113 either a molecule of interest or a control (i.e. the vehicle used for the corresponding molecule: DMSO
114 for ART, DHA and ATQ or PBS for CQ) and the volume made up to 1 mL with PBS. The entire setup
115 was incubated for 30 minutes at 37 °C. The tubes were then centrifuged and the supernatant
116 removed. The pellet was lysed by treatment with 100 μ L of a lysing solution (5 mM sodium
117 phosphate and 1 mM EDTA, pH 8.0) followed by two freezing/thawing cycles. Hundred microliters of
118 methanol were then added to each tube and the entire setup was centrifuged for 30 minutes at 4 °C
119 at 14,000 RPM to sediment the cell debris. The supernatant was taken for analysis. The amount of

120 $O_2^{\cdot-}$ produced was deduced from the integration of the peak of the chromatogram (Figure 2C)
121 corresponding to the 2-hydroxyethidium (2-OH-E^+ , m/z 330), a specific adduct formed under the
122 reaction of DHE with superoxide radicals, using the Xcalibur software and a calibration curve of the
123 standard (Figure 2D).

124 Results and Discussion

125 As interference with heme metabolism is known to be involved in the mechanism of action of
126 artemisinins [4,5] and quinolines [10], the ability of major antiparasitic drugs to interact with the
127 iron (II) to generate radicals was firstly investigated chemically by EPR spectroscopy using DMPO as
128 spin trap. The corresponding data (Figure 1A) clearly demonstrated that only artemisinin reacts with
129 Fe(II) to produce radicals while no radicals were generated with CQ or ATQ. The six-lined spectrum
130 recorded with artemisinin (Figure 1B) is characteristic of the DMPO-CH₃ adduct formed by the
131 reaction of DMPO with $\cdot\text{CH}_3$ produced when $\cdot\text{OH}$ reacts with DMSO.

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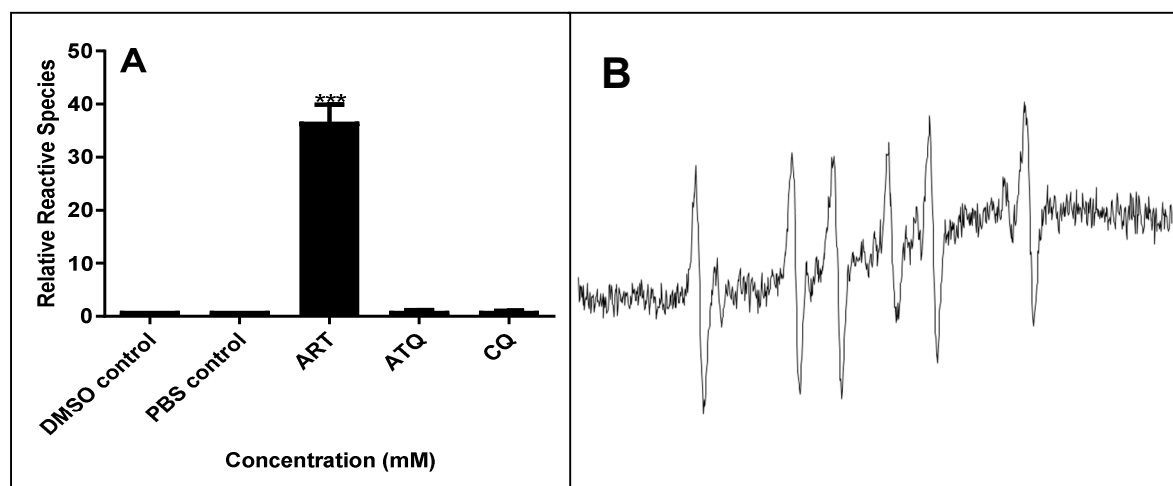
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138 **Figure 1:** (A) Production of hydroxyl radical deduced from the double integration of the EPR spectra
139 obtained in the presence of antimalarials (9 mM), Fe(II) salt (2 mM) and DMPO as spin trap (100
140 mM). Only ART interacts with Fe(II) to significantly generate hydroxyl radicals comparatively to the
141 DMSO-control. The results correspond to the mean of three independent experiments done in
142 triplicates.*** = statistically significant ($p < 0.001$). Artemisinin (ART); atovaquone (ATQ); chloroquine
143 (CQ). (B) EPR spectrum recorded with ART.

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145 The production of radicals, was then investigated on *Plasmodium falciparum* infected RBCs by
146 targeting $O_2^{\cdot-}$, the first radical formed by one electron reduction of oxygen. The total amounts of
147 intracellular $O_2^{\cdot-}$ were determined by quantification of 2-hydroxyethidium (2-OH-E^+) specifically
148 formed under reaction of the probe DHE with superoxide (m/z 330) (Figures 2C and 2D). The analysis
149 was performed after 30 min treatment of RBCs infected by the *P. falciparum* FcB1-Colombia strain
150 (5% parasitemia) with ART, DHA, ATQ and CQ at 0.5-500 nM (Figure 2A). The tested concentrations
151 was chosen according to their peak plasma concentration in patients. These results demonstrated
152 that artemisinins (ART and DHA) and ATQ generate significant amounts of superoxide (from $1.66 \pm$
153 0.10 for ATQ to 1.92 ± 0.11 fold for ART with the highest concentration tested). By contrast, CQ

154 treatment did not lead to any increase of superoxide in *Plasmodium* cultures, regardless of the drug
155 concentration used.

156 The uninfected RBCs control should be performed with RBCs from the same batch (same time and
157 age) like those used for the parasite culture. Therefore the control has to be performed with few
158 days old uninfected RBCs. However, uninfected RBCs can also produce $O_2^{\cdot-}$ when treated with
159 artemisinin [24]. For this reason the same experiment to quantify $O_2^{\cdot-}$ was then carried out with
160 concentrated cultures of *Plasmodium* in order to evaluate the amount of radicals specifically
161 originating from the infected RBCs. The infected RBCs were sorted by magnetic separation and the
162 analysis was performed after a 500 nM-treatment with ART, ATQ and CQ (Figure 2B). Increasing the
163 parasitaemia from 5% to 70 % induced a 10-fold boost (17 ± 5 to 157 ± 33 nM for the DMSO control
164 and 28 ± 9 to 299 ± 67 nM for ART) in the level of $O_2^{\cdot-}$ detected even in the absence of treatment
165 from the drugs under study (supplementary data, [Figure S1](#)), confirming the strong redox activity in
166 infected RBCs at the steady state. Moreover, by comparing the level of $O_2^{\cdot-}$ formed with or without
167 ART (supplementary data, [S1](#)), we estimated that the drug treatment led to a 60-fold higher
168 production of $O_2^{\cdot-}$ on infected RBCs than on uninfected erythrocytes. This result confirms that the
169 increased amount of $O_2^{\cdot-}$ recorded for ART in Figure 2A is mainly due to the effect of the drug on
170 infected RBCs. The data obtained with *Plasmodium* cultures at 70 % parasitemia, presented in Figure
171 2B, confirmed that ART and ATQ, but not CQ, induce a strong relative increase in superoxide in
172 infected RBCs. Even though the relative increase was only 2.0 ± 0.1 for ART and 1.9 ± 0.0 for ATQ,
173 that can be explained by the basal redox activity, obtained after infected RBCs sorting, which was 10
174 fold higher even in the absence of drug treatment (supplementary data, [Figure S1](#)).

175 CQ is an age-long antimalarial drug whose activity is mediated by interference with heme
176 metabolism [10,13]. It did not produce significant levels of $O_2^{\cdot-}$ on the FcB1-Colombia strain in both
177 conditions tested (Figure 2A and 2B). The lack of significant $O_2^{\cdot-}$ production from CQ on FcB1 could be
178 as a result of its lesser efficacy against this chloroquine-resistant strain as compared to the
179 chloroquine-sensitive counterparts [25]. Indeed, in chloroquine-resistant strains, CQ is constantly
180 effluxed from the food vacuole, the site of action of CQ [26], limiting its interaction with heme, which
181 consequently leads to heme polymerization and parasite survival. This action could limit the
182 availability of free heme, and consequently limiting the $O_2^{\cdot-}$ generation. To confirm this hypothesis,
183 the same analysis was carried out on a chloroquine-sensitive strain, F32-Tanzania (Figure 3). The
184 results demonstrated that a significant amount of $O_2^{\cdot-}$ (1.7 ± 0.1 fold of the PBS control) was
185 produced after 30 min of CQ treatment on F32-Tanzania, confirming the reduced effect of CQ on the
186 chloroquine-resistant strain reported in Figure 2. These data confirm that $O_2^{\cdot-}$ detected herein are
187 definitely linked with the antiplasmodial action of the tested molecules. However, the amount of $O_2^{\cdot-}$
188 was significantly lower than that observed with ART (1.7 ± 0.1 vs 2.7 ± 0.3 folds) in the same
189 conditions (Figure 3). Even though both drugs, CQ and ART, act, among other pathways, by inhibiting
190 the heme polymerisation, their pharmacokinetics and pharmacodynamics are quite different [4–
191 6,10,13,17] which consequently leads to varying production of superoxide.

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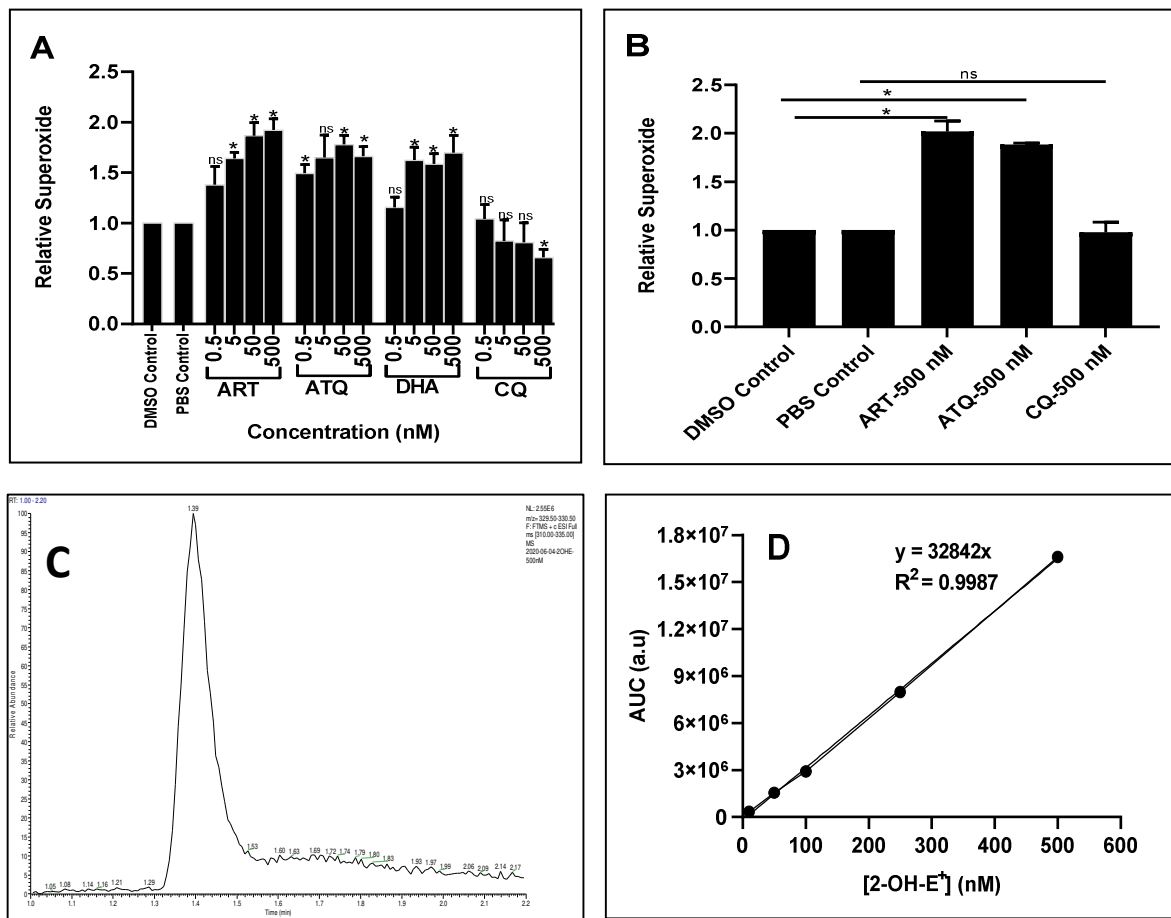
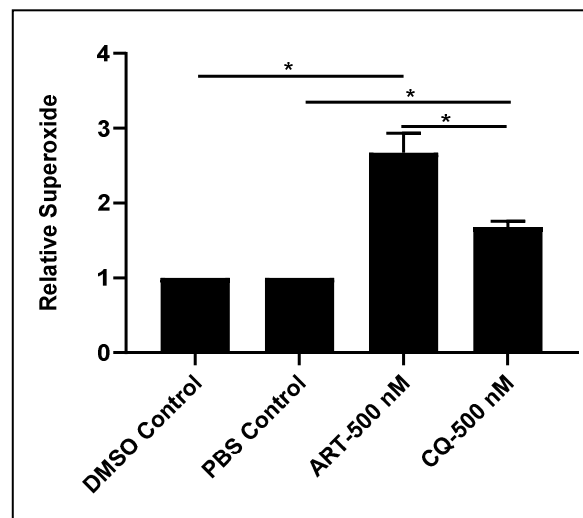


Figure 2: Quantification of superoxide radicals performed on the CQ-resistant strain, FcB1-Colombia in (A) non concentrated *Plasmodium* infected erythrocytes treated with increasing doses (0.5-500 nM) of artemisinin (ART), atovaquone (ATQ), dihydroartemisinin (DHA) and chloroquine (CQ), and (B) concentrated *Plasmodium* infected erythrocytes treated with ART, ATQ, and CQ at 500 nM. Artemisinins (ART and DHA) and ATQ generated significant amount of superoxide radicals ($p < 0.05$) compared to the control (DMSO for ART, DHA and ATQ; PBS for CQ) unlike chloroquine. (C) Chromatogram of 2-OH-E⁺ (D) Calibration curve of 2-OH-E⁺. The results correspond to the mean of six and three independent experiments done in triplicates for Figure 2A and Figure 2B, respectively. The level of significance was taken with reference to the control for each molecule. *= statistically significant ($p < 0.05$), ns=not significant.

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235 **Figure 3:** Quantification of superoxide radicals on a non-concentrated culture of the CQ-sensitive *P.*
236 *falciparum* strain, F32-Tanzania treated by ART and CQ at 500 nM. Both ART and CQ produced
237 significant ($p < 0.05$) levels of superoxide radicals when compared to their controls (DMSO for ART
238 and PBS for CQ). Moreover, the level of superoxide was significantly ($p < 0.05$) higher from ART than
239 CQ. The results correspond to the mean of three independent experiments done in triplicates.* =
240 statistically significant ($p < 0.05$).

241 The generation of reactive species under artemisinin treatment has been largely reported as their
242 main mechanism of action, *via* an interruption of heme metabolism [4,8,30–33]. The definitive
243 identification of these reactive species remained a subject of debate, since most of the quantification
244 of these reactive species in *Plasmodium* had been carried out by non-specific approaches using DCF
245 or CellRox fluorescence [6,8,19,20]. Therefore the present work demonstrates, for the first time, that
246 treatment of *Plasmodium* by artemisinins leads to superoxide generation. Superoxide radicals from
247 ART and DHA (the active metabolites of all artemisinin derivatives currently used) could be as a result
248 of: i) re-oxidation of the unpolymerized heme and consequent electron transfer to molecular oxygen
249 generating the superoxide radical-anion [34] and/or ii) alkylation of essential biomolecules which can
250 lead to cellular dysfunction such as mitochondrial dysfunction through the depolarization of the
251 mitochondria membrane [6,8,17], mitochondrial dysfunction being often associated with an
252 increased reactive oxygen species production [29].

253 Concerning atovaquone, the production of ROS under ATQ treatment has already been described in
254 cancer cells [35] but not in *Plasmodium*. The mode of action of ATQ is based on the inhibition of
255 mitochondrial cytochrome *bc1* complex *via* competitive inhibition of ubiquinol binding [15,36]. As a
256 consequence, ATQ induces the collapse of the mitochondrial membrane potential and blocks the
257 energy supply of the parasites [16,37]. Moreover, as the main metabolic function of cytochrome *bc1*
258 activity in *P. falciparum* appears to involve the regeneration of ubiquinone from ubiquinol, the
259 inhibition of this site might lead to the ubiquinol accumulation, which can undergo oxidation to
260 generate significant amount of superoxide radicals.

261

262 **Conclusion**

263 Superoxide radical was analytically and specifically detected here for the first time, as a major
264 reactive species produced by artemisinins, atovaquone, and at a lower level by chloroquine, in their
265 antiparasitic action. This radical is rapidly transformed chemically or enzymatically (by superoxide
266 dismutase) into hydrogen peroxide that reacts with iron(II) to form hydroxyl radical $\cdot\text{OH}$ (Fenton
267 reaction). This very reactive species having high oxidation potential reacts rapidly (lifespan
268 nanoseconds) with essential biomolecules (DNA, protein, lipids...) leading to the death of the
269 parasites which makes its intracellular detection extremely difficult.

270 Our findings clarify the specifics and identities of the reactive species, i.e. superoxide radical
271 produced by artemisinins and also categorize atovaquone as one of the antimalarials that acts *via*
272 intermediary reactive species generation. This study will help further in the understanding of the
273 mechanism of action of these molecules and help in the development of antimalarials, to fight drug-
274 resistance.

275

276 **Declaration of competing Interest**

277 None. The study design, data collection, analysis and interpretation, report writing, and the choice of
278 publishing this work are solely the responsibility of the authors.

279

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286

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