Prevalence of Plasmodium falciparum Pfcrt and Pfmdr1 alleles in settings with different levels of Plasmodium vivax co-endemicity in Ethiopia

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Abstract

Plasmodium falciparum and P. vivax co-exist at different endemicity levels across Ethiopia. For over two decades Artemether-Lumefantrine (AL) is the first line treatment for uncomplicated P. falciparum, while chloroquine (CQ) is still used to treat P. vivax. It is currently unclear whether a shift from CQ to AL for P. falciparum treatment has implications for AL efficacy and results in a reversal of mutations in genes associated to CQ resistance, given the high co-endemicity of the two species and the continued availability of CQ for the treatment of P. vivax. This study thus assessed the prevalence of Pfcrt-K76T and Pfmdr1-N86Y point mutations in P. falciparum. 18S RNA gene based nested PCR confirmed P. falciparum samples (N = 183) collected through community and health facility targeted cross-sectional surveys from settings with varying P. vivax and P. falciparum endemicity were used. The proportion of Plasmodium infections that were P. vivax was 62.2% in Adama, 41.4% in Babile, 30.0% in Benishangul-Gumuz to 6.9% in Gambella. The Pfcrt-K76T mutant haplotype was observed more from samples with higher endemicity of P. vivax as being 98.4% (61/62), 100% (31/31), 65.2% (15/23) and 41.5% (22/53) in Adama, Babile, Benishangul-Gumuz and Gambella, respectively. However, a relatively higher proportion of Pfmdr1-N86 allele (77.3–100%) were maintained in all sites. The observed high level of the mutant Pfcrt-76T allele in P. vivax co-endemic sites might require that utilization of CQ needs to be re-evaluated in settings co-endemic for the two species. A country-wide assessment is recommended to clarify the implication of the observed level of variation in drug resistance markers on the efficacy of AL-based treatment against uncomplicated P. falciparum malaria.

1. Introduction

Development and spread of anti-malaria drug resistance continued to be a stumbling-block in the fight against malaria. Plasmodium falciparum developed resistance to most of the antimalarials over the past 60 years (White, 2004). Resistance against Artemisinin combination therapies (ACT) (Carrara et al., 2013; Dondorp et al., 2009; Leang et al., 2013) is reported in Thai-Cambodian border, a historical ‘hotspot’ for multi-drug resistance parasite evolution, emergence and spread. Although ACTs retain high efficacy in sub-Saharan African countries including Ethiopia (Barnes et al., 2009; Tafile et al., 2018), recent reports are suggestive of the emergence of ACT tolerant P. falciparum in African settings (Xu et al., 2018).

One of the mechanisms for emergence of drug resistance in Plasmodium is acquisition of mutations and duplication in target and/or transporter genes. Artemether-Lumefantrine (AL) selects for wild-type
codons at the *P. falciparum* chloroquine resistance transporter (*Pfcrtr-K76*) and *P. falciparum* multidrug resistance 1 (*Pfmdr1*) alleles (Baliraine and Rosenthal, 2011; Sisowath et al., 2005) and its use is associated with increases in *Pfmdr1* gene copy number (Price et al., 2004). Variations were reported on the selective effects of different ACTs on single-nucleotide polymorphisms in *Pfcrtr* and *Pfmdr1*. A recent systemic review of 397 surveys in 30 countries in Africa documented that AL and arsunate-amodiaquine (ASAQ) exert opposing selective pressures and parasites under the selection pressure of one ACT tend to be more sensitive to the other (Okell et al., 2018). Higher proportion of *Pfmdr1*-86N and increases in its copy number have been reported in AL treated patients with parasite recrudescence (Venkatesan et al., 2014). It was noted that ASAQ selects the *Pfmdr1* mutant haplotypes, 86Y, Y184, and 1246Y (Venkatesan et al., 2014). Chloroquine is known to select the mutant Pfcrtr-K76T and the wild type Pfmdr1-N86Y haplotypes (Gботotosho et al., 2012). Therefore, in areas where both *P. falciparum* and *P. vivax* are co-endemic the continued use of CQ might result in pronounced different selective pressure and, as a consequence, different drug resistance profiles in communities.

Unlike most of Africa, *P. falciparum* (60%) co-exists with *P. vivax* (40%) in most settings in Ethiopia. Driven by the widespread CQ resistant *P. falciparum*, Ethiopia changed its treatment policy for *P. falciparum* from CQ to sulphadoxine-pyrimethamine (SP) in 1998 (Jima et al., 2005; Taffese et al., 2018); shortly after SP was replaced by AL as first-line therapy for uncomplicated falciparum malaria in 2004 (MOH, 2018; Taffese et al., 2018). Throughout this period, CQ continued to be used as first line treatment for *P. vivax* (MOH, 2018). This may have implications for selection of drug resistance marker genes. Here, we examined the prevalence of *Pfcrtr-K76T* and *Pfmdr1*-N86Y alleles in *P. falciparum* after two decades of AL implementation as first line treatment in areas with different *P. vivax* co-endemicity levels in Ethiopia.

2. Materials and methods

2.1. Study sites and samples

Study sites were selected based on reported difference in *P. vivax* and *P. falciparum* co-endemicity levels (Ministry of Health, 2016). Six Woredas (districts) representing different epidemiological settings from three regional administrative states (Gambella, Benishangul-Gumuz and Oromia) were included. Gambella region, with Abobo and Lare districts, is a P. falciparum dominated area (97% of all *Plasmodium* infections are *P. falciparum*) (Tssegay et al., 2014) with perennial transmission. Benishangul-Gumuz region, with Mao-Komo and Menge districts, is also *P. falciparum* dominated with relatively higher prevalence of *P. vivax* (10.1%) (Geleta and Ketema, 2016) and more seasonal transmission. The Oromia region study site districts of Babile and Adama are characterized by seasonal malaria transmission with co-endemicity for *P. falciparum* and *P. vivax* where *P. vivax* infections attributed to be 41.4% (Keffale et al., 2019) in the first and 62.2% (Tadesse et al., 2018) in the later district, respectively (Fig. 1 and Table 1). Oromia regional state has wider variation in the *P. vivax* and *P. falciparum* infection proportions due to its huge landmass and sampling was done in separate years i.e. Adama in 2016 and Babile in 2017, hence we have made separate treatment of the data from the study sites.

Study participants were recruited in community and health facility based cross-sectional surveys. Community based cross-sectional surveys were conducted in Babile district from July to November 2017 and from October to December 2016 in all other sites. In Adama passively-detected clinical malaria infected patients (n = 36) were recruited in addition to the community survey samples (n = 33). Finger prick blood samples (~300 µL) were collected from the study participants for malaria diagnosis using rapid diagnostic test (RDT) (First Response Malaria Ag (pLDH/HRP2, Combo RDT, Premier Medical Corporation Ltd., India) or microscopy and to prepare dried blood spots (DBS) on Whatman 3 MM filter paper (Whatman, Maidstone, UK). Socio-demographic and malariometric data were captured using pre-tested structured questionnaire.

2.2. Detection of Pfcrtr and Pfmdr1 polymorphisms

Study participants were diagnosed for malaria using thick blood smears and thin smears were used for species identification following Giemsa-staining by two experienced microbiologists who were independent and blind for the participants’ clinical status and RDT results. A third World health organization certified microbiologist was consulted in case of discordant results. Blood film slides were considered negative if no parasite was detected after examining 100 microscopic fields (Tadesse et al., 2018).

Furthermore, DNA was extracted from a 6 mm diameter punch of DBS using Chelex-Saponin extraction method as described elsewhere (Baidjoe et al., 2013); eluted DNA was stored at −20 °C until further use. Malaria species was confirmed with 18S based nested polymerase chain reaction (nPCR) as described elsewhere (Snounou et al., 1993). Samples that were confirmed to be *P. falciparum* mon-species infection using the 18S RNA nPCR (Snounou et al., 1993) were further amplified for the Pfcrtr-76 and Pfmdr1-86 genes using nPCR with outer (N1) and inner primer pairs (N2) (Supplement 1). The N2 products were assessed using restriction fragment length polymorphism (RFLP) to detect mutations at each locus (Djimdé et al., 2001; Vegia et al., 2006). Restriction enzymes used and conditions of digestion were as described elsewhere (UMSM, 2012). For Pfcrtr-76 codon, a known positive control of 3D7 (wild-type, Pfcrtr-76K allele) and negative control of Dd2 (mutant) were included in each reaction (kindly provided by the Ethiopian Public Health Institute). Restriction enzyme digested products were visualized with UV transilluminator after electrophoresis using 2% agarose gel (SIGMA-ALDRICH) with a no enzyme digest control run alongside positive controls, negative controls and test samples (Bio Rad, USA). Mixed haplotypes having both wild and mutant type were interpreted as combined band patterns of digested and undigested products identified per sample of DNA.

2.3. Ethics statement

The study protocol was approved by the National Research Ethical Review Committee (3.10|016|20), Institutional Ethical Review Board of the College of Natural Science at Addis Ababa University, and AHRI/ ALERT (Ref.No.SOM/DRERC/BCH005/2009, PO24/17). Written informed consent was obtained from each adult and parent/legal guardians for children younger than 18 years. Symptomatic patients were treated as per the national treatment guideline (MOH, 2018).

2.4. Statistical analysis

Both laboratory and field data were double entered. The cleaned data was analyzed using STATA 13 (StataCorp, TX, USA). The difference in prevalence among study sites was compared using Fisher’s exact test. Pairwise comparison, after Bonferroni correction, was run to test differences in distribution of the wild and mutant alleles between the study sites for both Pfcrtr-76 and Pfmdr1-86 codons. A *P*-value ≤ 0.05 was considered statistically significant.

3. Results

3.1. Characteristics of the study participants

A total of 183 samples from 148 asymptomatic and 35 symptomatic participants with *P. falciparum* infection by 18S nPCR were included in the study. Out of the 183 samples, 169 (92.3%) and 168 (91.8%) were successfully amplified for Pfcrtr-76 and Pfmdr1-86 codons, respectively. Adama was the only site where asymptomatic and symptomatic study participants were considered. There was no significant difference
among wild type and mutant haplotypes of the Pfcrt-76 codons between the asymptomatic (7.4%, 2/27) and symptomatic (8.6%, 3/35; P = 0.125) samples of Adama hence considered together in the subsequent analysis. Only wild type form of Pfmdr1 was detected in both groups.

3.2. Prevalence of Pfcrt-76 haplotypes varies between study sites and P. vivax co-endemicity

Overall, the wild type Pfcrt-K76 haplotype was detected in 23.7% (40/169) and the mutant Pfcrt-76T in 76.3% (129/169) of samples across sites. We observed a statistically significant difference in the prevalence of Pfcrt-76 codons among the study sites (P < 0.001): mutant (Pfcrt-76T) type was virtually fixed in Babile (100%, 31/31) and with near fixation at Adama (98.4%, 61/62) districts of Oromia region where P. vivax is highly endemic (41.4% and 62.2% of cases, respectively) (Keffale et al., 2019; Tadesse et al., 2018). On the other hand, a higher prevalence of the wild type (Pfcrt-K76) codon was found in Abobo and Lare districts of Gambella (58.5%, 31/53) and in Mao-Komo and Menge districts of Benishangul-Gumuz (34.8%, 8/23) (Table 1).

Table 1

Characteristics of study participants and frequency point mutations of P. falciparum chloroquine resistance transporter (Pfcrt-76) and multi drug resistance 1 (Pfmdr1-86) genes among samples from four sites in Ethiopia from 2016 to 2017.

| Characteristics | Gambella Total (N = 183) | Benishangul-Gumuz Total (N = 183) | Babile Total (N = 183) | Adama Total (N = 183) | P-value |
|-----------------|--------------------------|-----------------------------------|------------------------|-----------------------|---------|
| Age (years), Median (IQR) | 13(8–18) | 12(9–18) | 15(8–35) | 20(8–32) | 14(8–25) |
| Female sex, n (%) | 24(43.6) | 11(42.0) | 13(39.4) | 27(39.1) | 75(41.0) |
| Proportion of infections that are P. vivax, % | 2.6 a | 10.1 b | 41.4 c | 62.2 d | 100 |
| Amplified samples for Pfcrt-76 codon, n/N | 55/53 | 23/26 | 31/33 | 62/62 | 169/183 |
| Pfcrt-76T (Mutant), % (n/N) | 58.5 (31/53) | 34.8 (8/23) | 0.0 (0/31) | 1.6 (1/62) | 22.7(40/183) |
| Pfmdr1-86 (wild type), % (n/N) | 41.5 (22/53) | 65.2 (15/23) | 100.0 (31/31) | 98.4 (61/62) | 76.3(129/169) |
| Pfmdr1-86Y (Mutant), % (n/N) | 52/55 | 22/26 | 32/33 | 62/62 | 168/183 |
| Pfmdr1-N86 (wild type), % (n/N) | 90.4(47/52) | 77.3(17/22) | 100(0/32) | 100.0(62/62) | 94.1(158/168) |
| Pfmdr1-Y86 (Mutant), % (n/N) | 9.6(5/52) | 22.7(5/22) | 0(0/32) | 0(0/62) | 5.9(10/168) |
| IQR, interquartile range. | + asymptomatic cases (n = 33) & passively recruited clinical cases (n = 36). | + asymptomatic cases (n = 33) & passively recruited clinical cases (n = 36). | + asymptomatic cases (n = 33) & passively recruited clinical cases (n = 36). | + asymptomatic cases (n = 33) & passively recruited clinical cases (n = 36). | + asymptomatic cases (n = 33) & passively recruited clinical cases (n = 36). |

The proportion of infections that is P. vivax is very low (< 10%) in these settings (Geleta and Ketema, 2016; Tsegaye et al., 2014) (Table 1). After Bonferroni correction, differences in the proportion of Pfcrt-76T among the study sites was observed (P = 0.0342).

3.3. High prevalence of Pfmdr1-86 wild haplotype across the study sites

The overall prevalence of the mutant codon, Pfmdr1-86Y, was 5.9% (10/168). The wild type codon, Pfmdr1-N86, was found fixed (100%) in Babile and Adama districts with similar higher proportions in Abobo and Lare districts of Gambella (90.4%, 47/52) and Mao-Komo and Menge districts of Benishangul-Gumuz (77.3%, 17/22). The prevalence of the mutant type (Pfmdr1-86Y) was only 9.6% (5/52) and 22.7% (5/22) in the districts from Gambella and Benishangul-Gumuz, respectively. Moreover, the observed prevalence of the different haplotypes was significantly different among the study sites (P = 0.001) (Table 1). No difference was observed in the proportion of Pfmdr1-N86 in between study sites after Bonferroni correction (P = 1.0).
4. Discussion

The return of wild type alleles of CQ resistance marker genes has been reported across Africa following replacement of CQ by ACTs (Baraka et al., 2018; Kavishe et al., 2014; Okell et al., 2018; Venkatesan et al., 2014). The possible associations of these markers with ACT drug tolerance underline the need for continued surveillance for the success of malaria control program. In this study we assessed the prevalence of Pfcrt-K76T and Pfmdr1-N86Y codons from different P. falciparum and P. vivax co-endemicity settings in Ethiopia.

The current study has documented a higher frequency of Pfcrt-76T mutant haplotypes proportional to the endemic level of P. vivax as being 98.4%, 100%, 65.2% and 41.5% in samples from Adama, Babile, Benishangul-Gumuz and Gambella, respectively. Lower proportion of parasites with the mutant allele (Pfcrt-76T) was detected in samples from Gambella and Benishangul-Gumuz where P. falciparum is the dominant species. The nearly approaching fixation of Pfcrt-76T mutant haplotype in Adama and its fixation in Babile districts of Oromia region was in agreement with previous reports in Ethiopia (Golassa et al., 2014; Mula et al., 2011). This might be partly due to the high prevalence of P. vivax co-endemicity that probably lead to the continued utilization and easy access of CQ in these areas. Similar findings associating resistance markers with CQ use have been reported elsewhere: persisting high levels of mutant Pfcrt haplotypes in infections from Brazil and, in contrast, the re-appearance of wild type forms in Nigeria have been attributed to differences in the selective pressure by CQ use (Gbotosho et al., 2012). Moreover, the slow reappearance of CQ sensitive parasites harboring Pfcrt-76T haplotype in low P. vivax prevalence areas of Gambella and Benishangul-Gumuz corroborates observations from other African countries such as Malawi (Kublin et al., 2003), Côte d’Ivoire (Dagnogo et al., 2018), Zambia (Mwanza et al., 2016), Tanzania (Mohammed et al., 2013) and Kenya (Achieng et al., 2015).

Higher proportion of the wild type allele, Pfmdr1-N86, (77.3–100%), was detected in all sites; fixed in Babile and Adama. This finding was in line with previous reports from different parts of Ethiopia (Lo et al., 2017; Mekonnen et al., 2014; Mula et al., 2011). Earlier studies conducted more than a decade ago indicated a non-negligible level of the mutant form in Ethiopia (Eshevu et al., 2010; Schunk et al., 2006). This is probably due to the AL-regimen rolled out as first line treatment for P. falciparum infection across the study sites. In African settings, after decades of AL use a rise in the “NFD Pfsdr1 haplotypes at codons-86,184 and 1246 have been observed with a parallel decline in the “YYY” haplotypes of these codons (Duah et al., 2013; Okell et al., 2018; Sondo et al., 2016; Venkatesan et al., 2014). These studies found that the “NFD” haplotypes were associated with the reduced sensitivity of the parasite to AL treatment.

The observed difference across the study sites is plausibly associated with antimarial drug pressure as observed in other co-endemic settings. The re-emergence of genotypes such as Pfcrt-K76 and Pfmdr-1 codons-N86, 184F and 1246 after CQ withdrawal has been associated with selection of parasites with reduced sensitivity to AL (Achieng et al., 2015; Conrad et al., 2014; Dokomajilar et al., 2006; Sisowath et al., 2009) which may eventually lead to resistance (Ljolje et al., 2018; Sisowath et al., 2005; Venkatesan et al., 2014). Moreover, in settings where P. falciparum and P. vivax are sympatric where mixed species infections are common, the detection of P. falciparum is frequent following treatment of P. vivax with CQ (Heuchert et al., 2015; Mekonnen et al., 2014; Tajebe et al., 2014). Thus, the low CQ level to which the P. falciparum will be exposed might favor selective pressure.

The strength of this study is that it considered samples from different levels of P. vivax and P. falciparum co-endemicity (with varied CQ pressure) and both symptomatic and asymptomatic individuals. It is less likely to have a shift in proportion of infections due to P. vivax in the two years of sampling (2001 and 2017); the over decade national malaria control program data summary (2001–2016), documented no considerable change in the proportion of infections due to P. vivax in Ethiopia (Tafesse et al., 2018). The almost complete reversal of the wild haplotype, Pfmdr1-N86Y codon, in all our sites reinforce the claim that such phenomenon might be due to ACT based treatment. Thus, we suggest parallel surveillance of drug resistance markers to monitor the effects of the antimalarial-drugs deployed in areas where P. vivax and P. falciparum are co-endemic. The similarity in the drug resistance profile among asymptomatic individuals and clinical patients is suggestive of asymptomatic infections could serve as hidden reservoirs. Therefore, our finding also underpin the importance of involving asymptomatic reservoirs in the evaluation of drug resistance especially in areas approaching elimination (Nyunt et al., 2017).

This study would have been more comprehensive if clonality of infections and copy number variations (CNVs) of target genes were assessed. We reported mixed haplotypes for Pfcrt-76 (8.0%, 13/169) and Pfmdr1-86 (4.2%, 7/168). As the study was based on PCR-RFLP method alone ascertaining whether any of the two haplotypes were coming from the same genome or multi-clonal infections was difficult; hence we reported the mixed haplotypes together with the mutant proportions. Also, Pfmdr1-86 CNV is implicated for the emergence of P. falciparum diminished susceptibility to anti-malarial drugs, such as mefloquine, AS-MQ and AL combinations (Duah et al., 2013; Venkatesan et al., 2014).

In conclusion, after two decades of the replacement of CQ with AL for the treatment of uncomplicated falciparum malaria in Ethiopia, there is slow but site-specific reversal of the Pfcrt-K76 haplotype while the Pfmdr1-N86 wild type was almost fixed across study sites, a preliminary finding that calls the need for monitoring and responding to emerging signs of drug resistance to preserve the efficacy of anti-malarial drugs. Thus, we recommend country-wide assessments to clarify the implication of the observed level of variation in drug resistance markers on the efficacy of AL-based treatment against uncomplicated P. falciparum malaria.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpddr.2019.09.002.

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Conflicts of interest

None declared.

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