



**HAL**  
open science

## **Inclusion of gametocyte parameters in anti-malarial drug efficacy studies: filling a neglected gap needed for malaria elimination**

Rashad Abdul-ghani, Leonardo K. Basco, John C. Beier, Mohammed A. K. Mahdy

### **► To cite this version:**

Rashad Abdul-ghani, Leonardo K. Basco, John C. Beier, Mohammed A. K. Mahdy. Inclusion of gametocyte parameters in anti-malarial drug efficacy studies: filling a neglected gap needed for malaria elimination. *Malaria Journal*, 2015, 14 (413), 10.1186/s12936-015-0936-4 . hal-01236053

**HAL Id: hal-01236053**

**<https://amu.hal.science/hal-01236053>**

Submitted on 1 Dec 2015

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

OPINION

Open Access



# Inclusion of gametocyte parameters in anti-malarial drug efficacy studies: filling a neglected gap needed for malaria elimination

Rashad Abdul-Ghani<sup>1,2\*</sup>, Leonardo K. Basco<sup>3</sup>, John C. Beier<sup>4</sup> and Mohammed A. K. Mahdy<sup>1,2</sup>

## Abstract

Standard anti-malarial drug efficacy and drug resistance assessments neglect the gametocyte parameters in their protocols. With the spread of drug resistance and the absence of clinically proven vaccines, the use of gametocytocidal drugs or drug combinations with transmission-blocking activity is a high priority for malaria control and elimination. However, the limited repertoire of gametocytocidal drugs and induction of gametocytogenesis after treatment with certain anti-malarial drugs necessitate both regular monitoring of gametocytocidal activities of anti-malarial drugs in clinical use and the effectiveness of candidate gametocytocidal agents. Therefore, updating current protocols of anti-malarial drug efficacy is needed to reflect the effects of anti-malarial drugs or drug combinations on gametocyte carriage and gametocyte density along with asexual parasite density. Developing protocols of anti-malarial drug efficacy that include gametocyte parameters related to both microscopic and submicroscopic gametocytaemias is important if drugs or drug combinations are to be strategically used in transmission-blocking interventions in the context of malaria elimination. The present piece of opinion highlights the challenges in gametocyte detection and follow-up and discuss the need for including the gametocyte parameter in anti-malarial efficacy studies.

**Keywords:** *Plasmodium*, Gametocyte, Anti-malarial drug, Drug resistance, Efficacy study, Malaria elimination

## Background

There are several integrated approaches for the assessment of anti-malarial drug efficacy and drug resistance: therapeutic efficacy in symptomatic patients with uncomplicated malaria, in vitro/ex vivo assays, molecular markers of drug resistance, and measurement of plasma concentration of anti-malarial drugs [1, 2]. Clinical studies are the gold standard for assessing the efficacy of anti-malarial drugs, and their outcomes represent the primary data used for making malaria treatment policies by national and regional control programmes [3, 4]. Apart from the clinical assessment of therapeutic response to the drug or drug combinations, the parasitological parameters adopted in different protocols of clinical studies, including the standard World Health Organization

(WHO) protocols, only address the decrease in parasite density of asexual forms [5–8]. Parasitologically, therefore, drug efficacy studies do not consider the drug effect on gametocyte carriage and density but focus on asexual parasite density. This is attributed to the fact that clinical presentation of malaria is a direct consequence of the asexual erythrocytic stages and that gametocytes are not responsible for the clinical disease. Although these protocols are useful to measure the schizonticidal efficacy, they do not consider the gametocytocidal activity of the tested anti-malarial drug or drug combinations. The question remains as to why the gametocyte parameter is not routinely investigated during the 28–42 day follow-up period. The gametocytocidal action and transmission-blocking potential are not the major issues in most drug efficacy studies that primarily consider the schizonticidal action of anti-malarial drugs. Several clinical studies have focused on gametocytocidal action of different drugs [9–11], but once it is established, most researchers may

\*Correspondence: rashadqb@yahoo.com

<sup>2</sup>Tropical Disease Research Center, University of Science and Technology, Sana'a, Yemen

Full list of author information is available at the end of the article

not feel the need to re-assess gametocytocidal efficacy of those drugs.

At present, 8-aminoquinolines (primaquine and tafenoquine) are the only gametocytocides that are highly effective against gametocytes of all human malaria species. Artemisinin derivatives do not kill mature gametocytes of *Plasmodium falciparum*, but indirectly inhibit gametocyte development by killing immature gametocytes and rapidly killing asexual erythrocytic parasites before gametocytogenesis occurs [12]. Although primaquine has been shown to stop transmission before the disappearance of gametocytes from the peripheral blood on microscopy, its use as a gametocytocidal drug is associated with some risks, such as haemolytic toxicity among patients with glucose-6-phosphate dehydrogenase deficiency which occurs at high frequencies (3–30 %) in some endemic countries, hindering its use on a large scale in elimination strategies [13–15]. In addition, alternative gametocytocidal drugs, such as tafenoquine, are still under clinical investigation. Recently, Eziefula et al. [14] reported the lack of informativeness of gametocyte data in primaquine trials and proposed a strategic plan to optimize trial design for efficient interruption of malaria transmission. These authors also recommended the establishment of standard protocols to assess the efficacy of novel gametocytocidal agents, such as tafenoquine and methylene blue. This supports the present opinion piece to include the gametocyte parameter in standardized protocols of regular anti-malarial monitoring studies.

### **Is it necessary to include the gametocyte parameter in anti-malarial drug efficacy studies?**

Even if the drug is effective in clearing asexual parasitaemia and resolving malaria-associated signs and symptoms, gametocytogenesis can be initiated after the use of certain anti-malarial drugs, such as chloroquine and sulfadoxine-pyrimethamine [16]. Given that anti-malarial drug resistance is widespread and drug-resistant parasites are more likely to produce large numbers of gametocytes, compared to drug-sensitive parasites, the transmissibility of gametocytes carrying drug-resistant alleles is enhanced [10, 17–24]. The inclusion of gametocyte parameters in the standard tests used to regularly assess anti-malarial drug efficacy in such situations would be of great value to deter anti-malarial drug resistance.

To attain malaria elimination, anti-malarial drugs or drug combinations should not only clear the asexual parasite stages responsible for clinical disease but also clear the sexual stages that maintain its transmission. To address the need for the strategic use of anti-malarial drugs in blocking malaria parasite transmission, the parallel inclusion of the gametocyte parameter with asexual parasite density should be prioritized in drug efficacy

studies [12, 16]. Anti-malarial chemotherapy should specifically target gametocyte clearance to reduce or block parasite transmission and to prevent selection and spread of resistant strains [16, 25, 26].

It remains controversial whether the establishment in a clinical study that a certain anti-malarial drug has a gametocytocidal action is enough, ignoring the assessment of such action in subsequent efficacy studies. Several considerations suggest the necessity to regularly assess the gametocytocidal action of anti-malarial drugs in efficacy studies. First, the complexity of gametocytogenesis that involves the interaction of several host, environmental and biological factors [27, 28], including treatment with certain anti-malarial drugs, collectively leads to variability in gametocyte carriage and density. For instance, the gametocytocidal action of a drug in a certain geographical area could be different from another depending on certain factors such as the level of malaria endemicity and the immune status of exposed population. Second, there could be a seasonal variation in the rate of gametocytaemia in the same area [29], which requires further investigation of possible variations in the gametocytocidal action of anti-malarial drugs intended to interrupt malaria transmission in that area. Third, in the face of increasing resistance to anti-malarial drugs that favour the increase in gametocyte density and/or prevalence [30, 31], a regular monitoring of gametocytocidal activity of the drug in relation to the resistance situation to a drug becomes a priority to block parasite transmission and spread of drug resistance. A major stride in this respect is the ongoing analysis of *P. falciparum* gametocyte carriage after treatment with different artemisinin-based combination therapy (ACT) from regions with different endemicity, which is being carried out by the Gametocyte Carriage Study Group of the Worldwide Anti-malarial Resistance Network [32]. This initiative undertakes the determination of gametocyte density or prevalence at enrolment and during follow-up as an inclusion criterion. The main focus is on epidemiological factors associated with gametocyte carriage and clearance after treatment with different ACT across different countries. Accordingly, it will likely contribute to devising standardized protocols for the assessment of anti-malarial drug and drug combination efficacy that include the effects of different drug regimens on gametocyte carriage rate and duration within regular activities of national and regional malaria control programmes.

### **Challenges and prospects in gametocyte detection and follow-up**

One of the major challenges is the gap between the detectable gametocytes and infective level of gametocytaemia. Although the microscopic detection of

*Plasmodium* gametocytes may be as low as 10–20 gametocytes/ $\mu$ l [33], sub-microscopic gametocyte densities can infect vector mosquitoes [34–36]. In the standard WHO protocol for therapeutic efficacy, the microscopist reports whether gametocytes were observed while performing routine counts of asexual parasites, which is easier for the characteristic banana-shaped *P. falciparum* gametocytes compared to those of other species (which are rounded bodies that may be mistaken for mature asexual trophozoites). Sensitivity of microscopy is not enough for the detection of a low gametocytaemia [37]. In addition to being unrelated to clinical signs and symptoms of the disease, the longer time required to detect and count gametocytes is one of the major reasons to ignore routine counting of gametocytes during anti-malarial efficacy trials. Two types of counts are suggested to be performed on thick blood smears: a first count of asexual parasites against 200 white blood cells (WBCs) according to standard WHO protocols and a second count for gametocytes against at least 500 WBCs as previously reported [38, 39]. However, counting gametocytes against 500 WBCs should be revised and optimized as this comes down to about 20–30 high power fields, which seems to be far too little.

The question remains as for how long the presence of gametocytes should be monitored after treatment, i.e., the duration of gametocyte carriage. The follow-up intervals for the assessment of gametocyte carriage and gametocyte density should be different from those of asexual parasites because of the slower development of *P. falciparum* gametocytes (up to 10 days) compared to that of asexual erythrocytic stages [40]. In general, gametocytaemia is usually measured on a weekly basis starting on the day of treatment until the end of the fourth week of treatment when it peaks and then starts to decline [22]. Therefore, there is a need to establish the best chronological follow-up pattern that would even extend beyond that for asexual parasitaemia due to the relative persistence of gametocytes in the blood. The period of follow-up will be different, where asexual parasites should be counted according to standard WHO protocols (i.e., 28–42 days) whereas gametocytes should be screened at weekly intervals for a longer period, at least 42 days. However, optimization of the follow-up period for gametocytes is yet to be explored. It is noteworthy that an innovative magnetic fractionation approach for on-site counting of gametocytes in field studies has been introduced as an alternative to light microscopy with a sensitivity comparable to that of reverse transcriptase polymerase chain reaction (RT-PCR) [39].

In case of sub-microscopic infections where counts could not be performed, gametocytes can be detected and their load can be quantified using molecular techniques.

The adoption of specific molecular approaches, such as real-time RT-PCR for gametocytes, facilitates their detection and quantitation [41–43]. In line with the efforts devoted to eliminating malaria transmission, molecular detection of *Plasmodium* gametocytes could help in two directions: epidemiologically for uncovering the sub-microscopic human reservoir and clinically for monitoring gametocytocidal activity of transmission-blocking anti-malarial drugs. This is particularly important since masked or invisible infectious reservoir in endemic areas is much greater than that revealed by microscopy and it maintains malaria transmission [37, 44–47].

Attempts to discover innovative, rapid techniques for the detection of gametocytes could help overcome technical difficulties encountered in determining gametocytaemia by microscopy. This becomes feasible in the field with the introduction of easy, reliable filter-paper blood collection as well as loop-mediated isothermal amplification (LAMP) technique for the detection of low-density parasite gametocytes [48–51]. The development of a reverse transcriptase-LAMP for the detection of *P. falciparum* gametocytes in clinical specimens [49] may pave the way for the innovation of rapid, simple molecular tests for detection and quantitation of sub-microscopic gametocytes for discriminating between blocking and non-blocking agents and monitoring possible changes in the activity of available gametocytocidal drugs. Other approaches to explore include concentration of gametocytes prior to amplification by PCR, PCR using a high volume (i.e., 5–15 ml) of venous blood, quantitative nucleic acid sequence based amplification, PCR with intron-spanning primers, and alternative molecular targets with multiple copies [52–55]. The search for methodologies to overcome difficulties in detecting gametocytaemia in low transmission settings should be given attention. For instance, some authors have reported the utility of examining pooled samples in malaria diagnosis from different endemic settings [56–60]. This approach needs to be investigated with regard to detecting low-density gametocytaemia in clinical trials determining the gametocytocidal activity of anti-malarial drugs. However, further research, optimization and interpretation strategies are required to test the efficiency of sample pooling in gametocyte detection in different epidemiological settings. On a broader scale, more attention should be given to explore the utility of molecular tools as a complementary approach to provide data on gametocyte load retrospectively in relation to studies on therapeutic efficacy.

One of the best available measures to address the potential of malaria parasite transmission after treatment with anti-malarial drugs may be to adopt the area-under-the-curve (AUC) of gametocyte levels combining the duration of gametocyte carriage and their density [22], although

it may underestimate relationships between doses and therapeutic responses to gametocytocidal drugs in transmission-blocking studies [61]. For instance, the Four Artemisinin-Based Combinations Study Group used the AUC to assess gametocyte prevalence during follow-up of four artemisinin-based combinations in the treatment of uncomplicated malaria in seven African countries [62]. Despite the feasibility and applicability of the AUC in observational studies and clinical trials [22], its incorporation in measuring the gametocytocidal efficacy of anti-malarial drugs in routine anti-malarial drug efficacy studies is yet to be investigated. Therefore, follow-up protocols, monitoring both parasite density and gametocyte microscopic count or sub-microscopic load, have to be developed and evaluated for assessing anti-malarial drug or drug combination efficacies in different epidemiologic settings. In addition, the renewed interest in the assessment of the transmission-blocking activity of drugs and vaccines raises hope regarding the search for the best measures to evaluate their effects [61].

Apart from the determination of gametocyte carriage and gametocyte density after anti-malarial treatment, another challenge is infectivity measurement of gametocytes to vector mosquitoes. Transmissibility of infection from humans to mosquitoes is affected by a variety of host, parasite and vector factors [37]. Although it goes beyond the scope of the present opinion piece, it is noteworthy that there is no linear relationship between gametocyte density and infection rates of vector mosquitoes [63], and low-level or even sub-microscopic gametocytaemias can infect vector mosquitoes in certain settings [34–37]. In an attempt to devise tools to assess the transmissibility of infection, Joice et al. [64] recently developed and validated a method for the estimation of the relative quantities of asexual and sexual stages of *P. falciparum* that can be applied to infer maturity of gametocytes both in laboratory and in the field studies of malaria transmission.

Malaria elimination through drug-mediated transmission blocking of mature, viable male and female gametocytes to mosquitoes is a novel approach [65–67], which necessitates the adoption of appropriate strategies for assessing the transmission-blocking potential of the current and next generation of anti-malarials. The blocking potential of novel gametocytocidal agents can be determined by assessing the functional viability of drug-treated mature male and female gametocytes using *P. falciparum* dual gamete formation assay [68, 69]. Novel, high-throughput assays for assessing the functional viability of transmission stages of malaria parasites have recently been developed and validated to enable the identification of potent gametocytocidal agents that have a sterilizing effect on gametocytes, in particular on the more drug-sensitive mature male gametocytes [68, 70, 71]. Novel tools and approaches for the assessment of

gametocyte parameters in drug efficacy studies will be indispensable as an increasing number of countries and sub-regions aim to eliminate malaria in the coming years.

#### Authors' contributions

RA conceived of the idea. RA, LKB, JCB and MAKM contributed to the manuscript drafting and revision. All authors read and approved the final manuscript.

#### Author details

<sup>1</sup> Department of Parasitology, Faculty of Medicine and Health Sciences, Sana'a University, Sana'a, Yemen. <sup>2</sup> Tropical Disease Research Center, University of Science and Technology, Sana'a, Yemen. <sup>3</sup> Unité de Recherche 198, Unité de Recherche sur les Maladies Infectieuses et Tropicales Emergentes, Institut de Recherche pour le Développement, Faculté de Médecine La Timone, Aix-Marseille Université, Marseille, France. <sup>4</sup> Department of Public Health Sciences, University of Miami Miller School of Medicine, Miami, FL, USA.

#### Competing interests

The authors declare that they have no competing interests.

Received: 11 September 2015 Accepted: 9 October 2015

Published online: 19 October 2015

#### References

- Teja-Isavadharm P, Peggins JO, Brewer TG, White NJ, Webster HK, Kyle DE. *Plasmodium falciparum*-based bioassay for measurement of artemisinin derivatives in plasma or serum. *Antimicrob Agents Chemother*. 2004;48:954–60.
- Abdul-Ghani R, Al-Maktari MT, Al-Shibani LA, Allam AF. A better resolution for integrating methods for monitoring *Plasmodium falciparum* resistance to antimalarial drugs. *Acta Trop*. 2014;137:44–57.
- Vestergaard LS, Ringwald P. Responding to the challenge of antimalarial drug resistance by routine monitoring to update national malaria treatment policies. *Am J Trop Med Hyg*. 2007;77:153–9.
- WHO. Global report on antimalarial efficacy and drug resistance: 2000–2010. Geneva: World Health Organization; 2010.
- WHO. Chemotherapy of malaria and resistance to antimalarials. Report of a WHO Scientific Group. Geneva: World Health Organization; 1973.
- WHO. Assessment of therapeutic efficacy of antimalarial drugs for uncomplicated falciparum malaria in areas with intense transmission. Geneva: World Health Organization; 1996.
- WHO. Assessment and monitoring of antimalarial drug efficacy for the treatment of uncomplicated falciparum malaria. Geneva: World Health Organization; 2003.
- WHO. Methods for surveillance of antimalarial drug efficacy. Geneva: World Health Organization; 2009.
- Ringwald P, Meche FS, Basco LK. Short report: effects of pyronaridine on gametocytes in patients with acute uncomplicated falciparum malaria. *Am J Trop Med Hyg*. 1999;61:446–8.
- Sowunmi A, Fateye BA. *Plasmodium falciparum* gametocytaemia in Nigerian children: before, during and after treatment with antimalarial drugs. *Trop Med Int Health*. 2003;8:783–92.
- Kar PK, Dua VK, Gupta NC, Gupta A, Dash AP. *Plasmodium falciparum* gametocytaemia with chloroquine chemotherapy in persistent malaria in an endemic area of India. *Indian J Med Res*. 2009;129:299–304.
- Abdul-Ghani R, Beier JC. Strategic use of antimalarial drugs that block falciparum malaria parasite transmission to mosquitoes to achieve local malaria elimination. *Parasitol Res*. 2014;113:3535–46.
- Howes RE, Battle KE, Satyagraha AW, Baird JK, Hay SI. G6PD deficiency: global distribution, genetic variants and primaquine therapy. *Adv Parasitol*. 2013;81:133–201.
- Eziefula AC, Gosling R, Hwang J, Hsiang MS, Bousema T, von Seidlein L, et al. Rationale for short course primaquine in Africa to interrupt malaria transmission. *Malar J*. 2012;11:360.
- White NJ. Primaquine to prevent transmission of falciparum malaria. *Lancet Infect Dis*. 2013;13:175–81.

16. Abdul-Ghani R, Farag HF, Allam AF, Azazy AA. Measuring resistant-genotype transmission of malaria parasites: challenges and prospects. *Parasitol Res.* 2014;113:1481–7.
17. Price R, Nosten F, Simpson JA, Luxemburger C, Phaipun L, ter Kuile F, et al. Risk factors for gametocyte carriage in uncomplicated falciparum malaria. *Am J Trop Med Hyg.* 1999;60:1019–23.
18. Méndez F, Muñoz A, Carrasquilla G, Jurado D, Arévalo-Herrera M, Cortese JF, et al. Determinants of treatment response to sulfadoxine-pyrimethamine and subsequent transmission potential in falciparum malaria. *Am J Epidemiol.* 2002;156:230–8.
19. Méndez F, Herrera S, Murrain B, Gutierrez A, Moreno LA, Manzano M, et al. Selection of antifolate-resistant *Plasmodium falciparum* by sulfadoxine-pyrimethamine treatment and infectivity to *Anopheles* mosquitoes. *Am J Trop Med Hyg.* 2007;77:438–43.
20. Mockenhaupt FP, Teun Bousema J, Eggelte TA, Schreiber J, Ehrhardt S, Wassilew N, et al. *Plasmodium falciparum dhfr* but not *dhps* mutations associated with sulphadoxine-pyrimethamine treatment failure and gametocyte carriage in northern Ghana. *Trop Med Int Health.* 2005;10:901–8.
21. Mita T, Tanabe K, Kita K. Spread and evolution of *Plasmodium falciparum* drug resistance. *Parasitol Int.* 2009;58:201–9.
22. Méndez F, Muñoz A, Plowe CV. Use of area under the curve to characterize transmission potential after antimalarial treatment. *Am J Trop Med Hyg.* 2006;75:640–4.
23. Barnes KI, Little F, Mabuza A, Mngomezulu N, Govere J, Durrheim D, et al. Increased gametocytemia after treatment: an early parasitological indicator of emerging sulfadoxine-pyrimethamine resistance in falciparum malaria. *J Infect Dis.* 2008;197:1605–13.
24. Wongsrichanalai C, Sibley CH. Fighting drug-resistant *Plasmodium falciparum*: the challenge of artemisinin resistance. *Clin Microbiol Infect.* 2013;19:908–16.
25. Robert V, Molez JF, Trape JF. Gametocytes, chloroquine pressure, and the relative parasite survival advantage of resistant strains of falciparum malaria in west Africa. *Am J Trop Med Hyg.* 1996;55:350–1.
26. Sokhna CS, Trape JF, Robert V. Gametocytæmia in Senegalese children with uncomplicated falciparum malaria treated with chloroquine, amodiaquine or sulfadoxine + pyrimethamine. *Parasite.* 2001;8:243–50.
27. Talman AM, Domarle O, McKenzie FE, Ariey F, Robert V. Gametocytogenesis: the puberty of *Plasmodium falciparum*. *Malar J.* 2004;3:24.
28. Baker DA. Malaria gametocytogenesis. *Mol Biochem Parasitol.* 2010;172:57–65.
29. Giha HA, Elbashir MI, A-Elbasit IE, A-Gadir TM, ElGhazali G. Bimodal transmission of cerebral malaria and severe malarial anemia and reciprocal co-existence of sexual and asexual parasitemia in an area of seasonal malaria transmission. *Parasitol Res.* 2008;103:81–5.
30. Barnes KI, White NJ. Population biology and antimalarial resistance: the transmission of antimalarial drug resistance in *Plasmodium falciparum*. *Acta Trop.* 2005;94:230–40.
31. Ali E, Mackinnon MJ, Abdel-Muhsin AM, Ahmed S, Walliker D, Babiker HA. Increased density but not prevalence of gametocytes following drug treatment of *Plasmodium falciparum*. *Trans R Soc Trop Med Hyg.* 2006;100:176–83.
32. Worldwide Antimalarial Resistance Network. <http://www.wwarn.org/>.
33. White NJ. The role of anti-malarial drugs in eliminating malaria. *Malar J.* 2008;7(Suppl 1):S8.
34. Williamson KC, Keister DB, Muratova O, Kaslow DC. Recombinant Pfs230, a *Plasmodium falciparum* gametocyte protein, induces antisera that reduce the infectivity of *Plasmodium falciparum* to mosquitoes. *Mol Biochem Parasitol.* 1995;75:33–42.
35. Drakeley C, Sutherland C, Bousema JT, Sauerwein RW, Targett GA. The epidemiology of *Plasmodium falciparum* gametocytes: weapons of mass dispersion. *Trends Parasitol.* 2006;22:424–30.
36. Schneider P, Bousema JT, Gouagna LC, Otieno S, van de Vegte-Bolmer M, Omar SA, et al. Submicroscopic *Plasmodium falciparum* gametocyte densities frequently result in mosquito infection. *Am J Trop Med Hyg.* 2007;76:470–4.
37. Bousema T, Okell L, Felger I, Drakeley C. Asymptomatic malaria infections: detectability, transmissibility and public health relevance. *Nat Rev Microbiol.* 2014;12:833–40.
38. Babiker HA, Abdel-Wahab A, Ahmed S, Suleiman S, Ranford-Cartwright L, Carter R, et al. Detection of low level *Plasmodium falciparum* gametocytes using reverse transcriptase polymerase chain reaction. *Mol Biochem Parasitol.* 1999;99:143–8.
39. Karl S, Davis TM, St-Pierre TG. A comparison of the sensitivities of detection of *Plasmodium falciparum* gametocytes by magnetic fractionation, thick blood film microscopy, and RT-PCR. *Malar J.* 2009;8:98.
40. Lobo CA, Kumar N. Sexual differentiation and development in the malaria parasite. *Parasitol Today.* 1998;14:146–50.
41. Oesterholt MJ, Alifrangis M, Sutherland CJ, Omar SA, Sawa P, Howitt C, et al. Submicroscopic gametocytes and the transmission of antifolate-resistant *Plasmodium falciparum* in Western Kenya. *PLoS One.* 2009;4:e4364.
42. Babiker HA, Schneider P. Application of molecular methods for monitoring transmission stages of malaria parasites. *Biomed Mater.* 2008;3:034007.
43. Lima NF, Bastos MS, Ferreira MU. *Plasmodium vivax*: reverse transcriptase real-time PCR for gametocyte detection and quantitation in clinical samples. *Exp Parasitol.* 2012;132:348–54.
44. Abdel-Wahab A, Abdel-Muhsin AM, Ali E, Suleiman S, Ahmed S, Walliker D, et al. Dynamics of gametocytes among *Plasmodium falciparum* clones in natural infections in an area of highly seasonal transmission. *J Infect Dis.* 2002;185:1838–42.
45. Ouedraogo AL, Bousema T, Schneider P, de Vlas SJ, Ilboudo-Sanogo E, Cuzin-Ouattara N, et al. Substantial contribution of submicroscopical *Plasmodium falciparum* gametocyte carriage to the infectious reservoir in an area of seasonal transmission. *PLoS One.* 2009;4:e8410.
46. Karl S, Gurarie D, Zimmerman PA, King CH, StPierre TG, Davis TM. A sub-microscopic gametocyte reservoir can sustain malaria transmission. *PLoS One.* 2011;6:e20805.
47. Okell LC, Bousema T, Griffin JT, Ouedraogo AL, Ghani AC, Drakeley CJ. Factors determining the occurrence of submicroscopic malaria infections and their relevance for control. *Nat Commun.* 2012;3:1237.
48. Abdul-Ghani R, Al-Mekhlafi AM, Karanis P. Loop-mediated isothermal amplification (LAMP) for malarial parasites of humans: would it come to clinical reality as a point-of-care test? *Acta Trop.* 2012;122:233–40.
49. Buates S, Bantuchai S, Sattabongkot J, Han ET, Tsuboi T, Udomsangpetch R, et al. Development of a reverse transcription-loop-mediated isothermal amplification (RT-LAMP) for clinical detection of *Plasmodium falciparum* gametocytes. *Parasitol Int.* 2010;59:414–20.
50. Kuamsab N, Putaporntip C, Pattanawong U, Jongwutiwes S. Simultaneous detection of *Plasmodium vivax* and *Plasmodium falciparum* gametocytes in clinical isolates by multiplex-nested RT-PCR. *Malar J.* 2012;11:190.
51. Jones S, Sutherland CJ, Hermsen C, Arens T, Teelen K, Hallett R, Corran P, et al. Filter paper collection of *Plasmodium falciparum* mRNA for detecting low-density gametocytes. *Malar J.* 2012;11:266.
52. Schneider P, Schoone G, Schallig H, Verhage D, Telgt D, Eling W, et al. Quantification of *Plasmodium falciparum* gametocytes in differential stages of development by quantitative nucleic acid sequence-based amplification. *Mol Biochem Parasitol.* 2004;137:35–41.
53. Ribaut C, Berry A, Chevalley S, Reybier K, Morlais I, Parzy D, et al. Concentration and purification by magnetic separation of the erythrocytic stages of all human *Plasmodium* species. *Malar J.* 2008;7:45.
54. Wampfler R, Mwingira F, Javati S, Robinson L, Betuela I, Siba P, et al. Strategies for detection of *Plasmodium* species gametocytes. *PLoS One.* 2013;8:e76316.
55. Hofmann N, Mwingira F, Shekalaghe S, Robinson LJ, Mueller I, Felger I. Ultra-sensitive detection of *Plasmodium falciparum* by amplification of multi-copy subtelomeric targets. *PLoS Med.* 2015;12:e1001788.
56. Hsiang MS, Lin M, Dokomajilar C, Kemere J, Pilcher CD, Dorsey G, et al. PCR-based pooling of dried blood spots for detection of malaria parasites: optimization and application to a cohort of Ugandan children. *J Clin Microbiol.* 2010;48:3539–43.
57. Taylor SM, Juliano JJ, Trottman PA, Griffin JB, Landis SH, Kitsa P, et al. High-throughput pooling and real-time PCR-based strategy for malaria detection. *J Clin Microbiol.* 2010;48:512–9.
58. Lima GF, Levi JE, Geraldi MP, Sanchez MC, Segurado AA, Hristov AD, Inoue J, et al. Malaria diagnosis from pooled blood samples: comparative analysis of real-time PCR, nested PCR and immunoassay as a platform for the molecular and serological diagnosis of malaria on a large-scale. *Mem Inst Oswaldo Cruz.* 2011;106:691–700.
59. Congpuong K, Saejeng A, Sug-Aram R, Aruncharun S, Darakapong A, Meshnick SR, et al. Mass blood survey for malaria: pooling and real-time

- PCR combined with expert microscopy in north-west Thailand. *Malar J*. 2012;11:288.
60. Rogawski ET, Congpuong K, Sudathip P, Satimai W, Sug-aram R, Aruncharus S, et al. Active case detection with pooled real-time PCR to eliminate malaria in Trat province, Thailand. *Am J Trop Med Hyg*. 2012;86:789–91.
  61. White NJ, Ashley EA, Reicht J, Delves MJ, Ruecker A, Smithuis FM, et al. Assessment of therapeutic responses to gametocytocidal drugs in *Plasmodium falciparum* malaria. *Malar J*. 2014;13:483.
  62. Four Artemisinin-Based Combinations Study Group. A head-to-head comparison of four artemisinin-based combinations for treating uncomplicated malaria in African children: a randomized trial. *PLoS Med*. 2011;8:e1001119.
  63. Churcher TS, Bousema T, Walker M, Drakeley C, Schneider P, Ouedraogo AL, et al. Predicting mosquito infection from *Plasmodium falciparum* gametocyte density and estimating the reservoir of infection. *Elife*. 2013;2:e00626.
  64. Joice R, Narasimhan V, Montgomery J, Sidhu AB, Oh K, Meyer E, et al. Inferring developmental stage composition from gene expression in human malaria. *PLoS Comput Biol*. 2013;9:e1003392.
  65. Sinden RE. Malaria, sexual development and transmission: retrospect and prospect. *Parasitology*. 2009;136:1427–34.
  66. Burrows JN, Leroy D, Lotharius J, Waterson D. Challenges in antimalarial drug discovery. *Future Med Chem*. 2011;3:1401–12.
  67. Sinden RE, Carter R, Drakeley C, Leroy D. The biology of sexual development of *Plasmodium*: the design and implementation of transmission-blocking strategies. *Malar J*. 2012;11:70.
  68. Ruecker A, Mathias DK, Straschil U, Churcher TS, Dinglasan RR, Leroy D, et al. A male and female gametocyte functional viability assay to identify biologically relevant malaria transmission-blocking drugs. *Antimicrob Agents Chemother*. 2014;58:7292–302.
  69. Reader J, Botha M, Theron A, Lauterbach SB, Rossouw C, Engelbrecht D, et al. Nowhere to hide: interrogating different metabolic parameters of *Plasmodium falciparum* gametocytes in a transmission blocking drug discovery pipeline towards malaria elimination. *Malar J*. 2015;14:213.
  70. Delves MJ, Ramakrishnan C, Blagborough AM, Leroy D, Wells TN, Sinden RE. A high-throughput assay for the identification of malarial transmission-blocking drugs and vaccines. *Int J Parasitol*. 2012;42:999–1006.
  71. Delves MJ, Ruecker A, Straschil U, Lelièvre J, Marques S, Lopez-Barragan MJ, et al. Male and female *Plasmodium falciparum* mature gametocytes show different responses to antimalarial drugs. *Antimicrob Agents Chemother*. 2013;57:3268–74.

**Submit your next manuscript to BioMed Central  
and take full advantage of:**

- Convenient online submission
- Thorough peer review
- No space constraints or color figure charges
- Immediate publication on acceptance
- Inclusion in PubMed, CAS, Scopus and Google Scholar
- Research which is freely available for redistribution

Submit your manuscript at  
[www.biomedcentral.com/submit](http://www.biomedcentral.com/submit)

