Incrimination of *Anopheles (Anopheles) intermedius* Peryassú, *An. (Nyssorhynchus) nuneztovari* Gabaldón, *An. (Nys.) oswaldoi* Peryassú as natural vectors of *Plasmodium falciparum* in French Guiana

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Anopheles darlingi *Root is the major vector of human malaria in the Neotropics and has been considered to be the sole malaria vector in French Guiana. The presence of other potential vectors suggests that malaria may be transmitted by other species under certain conditions. From 2006-2011, all anopheline specimens collected from 11 localities were assayed to determine if the* Plasmodium *circumsporozoite protein was present. In addition to* An. darlingi*, we found* Anopheles oswaldoi*,* Anopheles intermedius *and* Anopheles nuneztovari *specimens that were infected with* Plasmodium *sp. Further investigations on the behaviour and ecology of* An. oswaldoi*,* An. intermedius *and* An. nuneztovari *are necessary to determine their role in malaria transmission in French Guiana.*

Key words: *An. intermedius* - *An. nuneztovari* - *An. oswaldoi* - malaria vector - French Guiana

Anopheles darlingi Root is the major vector of human malaria in the Neotropics. In French Guiana, this anopheline species has been considered the sole vector of malaria for more than 50 years because of its high densities, high levels of anthropophilic behaviour and natural infectivity over a wide geographic range (Floch & Abonnenc 1943b, Mouchet et al. 1989, Claustre et al. 2001). Guianan populations of *Anopheles aquasalis* and *Anopheles triannulatus,* both known malaria vectors in South America (de Arruda et al. 1986, de Oliveira-Ferreira et al. 1990, Galardo et al. 2007, Sinka et al. 2010), were also studied by Floch and Abonnenc (1943a, 1944), and the capability of these mosquitoes to transmit *Plasmodium* parasites was demonstrated. However, no naturally infected specimen of these species was found in French Guiana. *Anopheles neivai*, another potential vector (Gutierrez et al. 2008), was suspected by Pajot et al. (1978) to transmit malaria in the Upper Oyapock valley based on observations of malaria cases, the high density of this species and the absence of *An. darlingi*. However, no infected specimens of this species have yet been identified. Therefore, all investigations appeared to confirm that *An. darlingi* was the only vector of *Plasmodium falciparum*, *Plasmodium vivax* and *Plasmodium malariae* (Mouchet et al. 1989, Claustre et al. 2001, Girod et al. 2008, 2011, Hiwat et al. 2009). However, certain malaria transmission patterns are still far from clear (Carme et al. 2009) and the presence of other anopheline species, such as *Anopheles braziliensis*, *Anopheles intermedius, Anopheles mediopunctatus* s.l.*, Anopheles nuneztovari* s.l.*, Anopheles oswaldoi* s.l.*, Anopheles strodei and An. triannulatus* s.l., known as primary, secondary or occasional malaria vectors across South America, suggests that other anopheline species may transmit malaria parasites in French Guiana (Panday 1977, de Arruda et al. 1986, Hayes et al. 1987, de Oliveira-Ferreira et al. 1990, Branquinho et al. 1993, Quinones et al. 2006, Galardo et al. 2007). Therefore, the collections performed by our team since 2006 have involved a systematic search for *Plasmodium* sporozoites in anopheline species. Preliminary results documenting *An. intermedius* and *An. nuneztovari* s.l. specimens that were naturally infected by *P. falciparum* have previously been cited in Carme et al. (2009). These findings are strengthened by the data and overall analysis presented here.

From 2006-2011, 11 localities were selected within the framework of various research programmes. The collection sites were distributed along the coastal area, where malaria transmission occurs sporadically and along the Maroni and the Oyapock valleys, where malaria is endemic (Figure). Different protocols were used to collect mosquitoes. Human landing collections (HLC) were performed from 6:00 am-8:00 am and 5:00 pm-7:00 pm (HLC-1), from 5:00 am-7:00 am, 9:00 am-11:00 am, 3:00 pm-5:00 pm and 6:00 pm-10:00 pm (HLC-2) or overnight (HLC-3). Animal bait (AB) was used overnight or during the day. Light traps (LT), LTs plus human bait, Mosquito Magnet (Woodstream Corporation, Lititz, PA, USA) traps and exposure-free bednet traps were used overnight (6:00 pm-6:00 am) (Supplementary data). Collections were made within villages or in the surrounding crop fields and forest. Female anopheline mosquitoes were individually labelled to reflect the site, mode and time of capture. Morphological identification was based on the keys of Shannon (1933), Floch and Abonnenc (1951), Forattini (1962), Faran (1980), Faran and Linthicum (1981), Linthicum (1988) and on unpublished observations from Dr Bruce Harrison to distinguish *An.*

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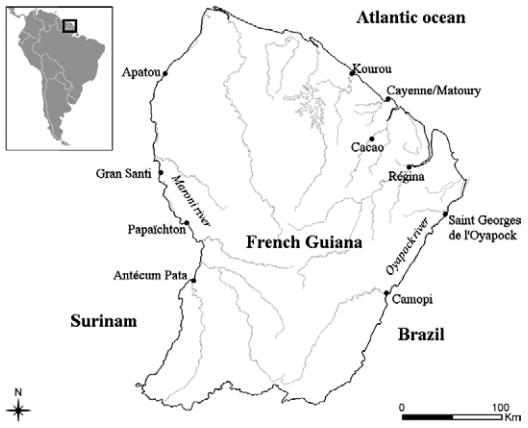
intermedius from *Anopheles apicimacula*. The head and thorax of the anopheline females were tested with enzyme-linked-immunosorbent assays for *P. falciparum*, *P. vivax* (VK210 and VK247 variant epitopes) and *P. malariae* circumsporozoite proteins according to Burkot et al. (1984), as modified by Wirtz et al. (1987, 1992).

A total of 2,227 anopheline females were assayed for the presence of *Plasmodium* circumsporozoites. *An. darlingi* (n = 929) was the most abundant species collected (Table). The other potential malaria vectors found (Supplementary data) were *An. oswaldoi* s.l. (n = 483), *An. intermedius* (n = 246), *An. braziliensis* (n = 190), *An. nuneztovari* s.l. (n = 145) and *An. triannulatus* s.l. (n = 68) (Table I). Two specimens of *An. darlingi* tested positive for *P. vivax* VK210, corresponding to an infection percentage of 0.22% (Supplementary data). These two infected females were both collected with the human-landing method between 6:00 pm-10:00 pm. The first female was captured in a forest camp in the Camopi area on 26 June 2007. The second infected female was caught in a crop field near Saint Georges de l'Oyapock on 5 May 2009. It is especially interesting that three additional highly abundant species tested positive for *P. falciparum* circumsporozoites: *An. oswaldoi* s.l. (n = 1), *An. intermedius* (n = 3) and *An. nuneztovari* s.l. (n = 1). Based on these results, 0.21% of *An. oswaldoi* s.l., 1.22% of *An. intermedius* and 0.69% of *An. nuneztovari* s.l. specimens collected were infected by *P. falciparum*. The infected *An. oswaldoi* s.l. specimen was collected with the Mosquito Magnet® trap in the forest near the village of Camopi. The infected *An. nuneztovari* s.l. specimen was caught using AB in the forest near the village of Saint Georges de l'Oyapock. The infected *An. intermedius* specimens were collected with the human-landing method between 6:00 pm-10:00 pm in the forest near the village of Saint Georges de l'Oyapock (n = 2) and in a crop field near the village of Cacao (n = 1). No other mosquito species naturally infected by *Plasmodium* species were found.



Location of collection sites in French Guiana.

The primary mosquito collection activity since 2006 was conducted in areas in French Guiana where the malaria transmission patterns are variable: along the littoral zone, where malaria cases are sporadic, along the border with Suriname in the Maroni valley, where the number of cases has drastically decreased during the past few years, and along the border with Brazil in the Oyapock valley,

TABLE

List of anopheline females tested for *Plasmodium* infection, number of specimen tested and number of specimen found infected for *Plasmodium falciparum*, *Plasmodium vivax* variant 210, *P. vivax* variant 247 and *Plasmodium malariae*

Anopheles species	n	*P. falciparum* n (%)	*P. vivax* 210 n (%)	*P. vivax* 247 n (%)	*P. malariae* n (%)
Anopheles darlingi	929	-	2 (0.22)	-	-
Anopheles oswaldoi s.l.	483	1 (0.21)	-	-	-
Anopheles intermedius	246	3 (1.22)	-	-	-
Anopheles braziliensis	190	-	-	-	-
Anopheles nuneztovari s.l.	145	1 (0.69)	-	-	-
Anopheles triannulatus s.l.	68	-	-	-	-
Anopheles sp.	41	-	-	-	-
Anopheles acanthotorynus/nimbus	42	-	-	-	-
Anopheles mediopunctatus s.l.	29	-	-	-	-
Anopheles ininii	19	-	-	-	-
Anopheles aquasalis	17	-	-	-	-
Anopheles peryassui	11	-	-	-	-
Anopheles minor	3	-	-	-	-
Anopheles neivai	3	-	-	-	-
Anopheles argyritarsis	1	-	-	-	-
Total	2,227	5	2	-	-

where the malaria transmission pattern is still not clear (Carme et al. 2009). The present work confirms (i) the role of *An. darlingi* as a malaria vector and (ii) the suspected presence of other *Anopheles* species that are naturally infected by *Plasmodium* spp in French Guiana.

An. darlingi was the most abundant species of the study. Of the specimens collected, 0.22% were infected with and could transmit *P. vivax*. This percentage is lower than those obtained for *An. intermedius* (1.22%) and *An. nuneztovari* (0.69%), but does not challenge the status of *An. darlingi* as the principal malaria vector in French Guiana. Indeed, in many previous studies performed in this region, *An. darlingi* was collected in high densities, had a high sporozoite index and was the only species naturally infected by the four *Plasmodium* sp. and variants, especially along the border with Suriname in the Maroni valley (Girod et al. 2008, Hiwat et al. 2009, Fouque et al. 2010). In our study, specimens of this species infected by *P. vivax* were found along the Oyapock River, where this parasite causes most cases of malaria (Carme et al. 2009, Girod et al. 2011), whereas the other anophelines carried *P. falciparum*. Even if our dataset does not furnish conclusive evidence, the documented parasite infections define a pattern in which the status of *An. darlingi* as the major vector is certain and in which *An. intermedius*, *An. nuneztovari* and *An. oswaldoi* may play local roles in *P. falciparum* transmission.

It is rare to find and document a naturally infected *An. intermedius*. de Arruda (1986) found that 3.3% of the specimens tested contained oocysts in their midguts. Galardo et al. (2007) found the four *Plasmodium* species and variants in four distinct *An. intermedius* populations in the neighbouring state of Amapá, Brazil, but observed a low inoculation rate for this species. Even if little is known about the role of *An. intermedius* in malaria transmission, vigilance has always been required for this vector (dos Santos et al. 2005, Sinka et al. 2010). Our study found *An. intermedius* specimens that were naturally infected by *P. falciparum* in Saint Georges de l'Oyapock, at the Brazilian border. However, no study has yet demonstrated a role for this mosquito species in malaria transmission. In addition, this species is often described as exophilic or zoophilic and is found in sylvatic or perisylvatic environments (Forattini 1962, Zimmerman et al. 2006, Galardo et al. 2007). It is probable that contact between this species and humans is occasional and could occur in households or camps near the forest. *An. oswaldoi* s.l. has been identified as a secondary or local vector in many areas of South America (Hayes et al. 1987, Branquinho et al. 1993, Mouchet et al. 2004, Quinones et al. 2006, Sinka et al. 2010). The species complex includes at least four species (Marrelli et al. 1999) that can transmit *P. falciparum, P. vivax* variants and *P. malariae* (Hayes et al. 1987, Branquinho et al. 1993, Quinones et al. 2006). The biting behaviour of these mosquitoes is often described as exophilic and zoophilic. In this study, we found one specimen that was naturally infected with *P. falciparum* in a forested area near Camopi. However, we did not identify the species within the complex and the behavioural patterns of this species remain unknown. *An. nuneztovari* s.l. is described as a primary or secondary vector (Hayes et al. 1987, Tadei & Thatcher 2000, Mouchet et al. 2004, Quinones et al. 2006, Moreno et al. 2007, Sinka et al. 2010). Heterogeneous behaviours and variable vectorial capacities throughout the distribution of this mosquito taxon may be explained by the presence of a complex of species (Sinka et al. 2010), in which five genetic lineages are currently identified (Mirabello & Conn 2008). We did not identify species within the *An. oswaldoi* s.l. complex and the behavioural patterns of this group remain unknown. Based on the literature, we can hypothesise that the populations from French Guiana resemble those from Brazil and Suriname. Exophilic, exophagic and zoophilic behaviours have been observed in this region of South America (Panday 1977, Montoya-Lerma et al. 2011), whereas anthropophilic and endophagic behaviours are commonly found in Peru, Colombia and Venezuela (Montoya-Lerma et al. 2011). In addition, Mirabello and Conn (2008) identified lineage 1 in northeastern and central Amazonia, including the Guiana shield. In French Guiana, data on *An. intermedius*, *An. oswaldoi* s.l. and *An. nuneztovari* s.l. are still scarce. Further insights on the behaviour, ecology and genetics of these species are needed to confirm the roles that the species play in malaria transmission.

In addition to the present work, studies on other species known to be possible vectors in neighbouring countries (e.g., *An. triannulatus* s.l. or *An. aquasalis)* would complement the approach taken by our research (Charlwood & Wilkes 1981, Rubio-Palis 1994, Galardo et al. 2007, Sinka et al. 2010). Mosquito collections performed in the inland part of French Guiana would serve to complete the *Anopheles* species list in French Guiana. Indeed, it is surprising that species known as malaria vectors in the Brazilian Amazon and Suriname (e.g., the Albitarsis complex) have not yet been encountered in French Guiana.

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Localities, year, dates and methods of mosquito collections

Locality	Year	Date (day month)	Collection method
Antécum Pata	2007	1-3 June	HLC-3
Apatou	2007	31 May-1 June	HLC-3
Cacao	2007	26-30 November, 10-14 December	HLC-2, LT
	2008	25-29 February, 8-12 September	HLC-2, LT, LT-HB
Camopi	2007	18-29 June	HLC-2, LT
	2008	15-17 January	HLC-3
		12-16 May, 7-11 July	HLC-3, LT, EFT, MM, LT-HB
		15-19 December	HLC-2, LT
	2009	5-9 January	HLC-2, LT
		11-14 June	HLC-3, LT, EFT, MM
Cayenne	2006	9-12 October, 23-26 October	HLC-1, AB, LT
	2007	21-24 May, 11-14 June	HLC-1, AB, LT
Gran Santi	2007	3-13 July	HLC-2, LT
	2008	21-25 July, 4-8 August	HLC-2, LT
Kourou	2010	8-11 February, 22-25 March	HLC-2C, LT
	2011	14-17 February	HLC-2C, LT
Matoury	2010	8-11 March, 6-9 April	HLC-2, LT
	2011	28-31 March	HLC-2, LT
Papaïchton	2007	3-5 June	HLC-3
Régina	2009	4-5 June	HLC-3, LT, EFT, LT-HB
	2010	22-25 February, 19-22 April	HLC-2, LT
	2011	14-17 March	HLC-2, LT
Saint Georges de l'Oyapock	2006	6-10 November	HLC-3, LT
		20-23 November, 4-7 December	HLC-1, AB, LT
	2007	9-12 May, 23-26 July	HLC-1, AB, LT
	2009	20-23 April, 4-7 May	HLC-2, LT
		2-4 June	HLC-3, LT, EFT, LT-HB

AB: overnight and day animal baits; EFT: overnight exposure-free bednet trap; HLC-1: human landing collections in the range of 06:00 am-08:00 am and 05:00 pm-07:00 pm; HLC-2: in the range of 05:00 am-07:00 am, 09:00 am-11:00 am, 03:00 pm-05:00 pm and 06:00 pm-10:00 pm; HLC-3: overnight; LT: overnight light-trap; LT-HB: overnight LT plus human bait; MM: overnight Mosquito Magnet®.