

# POPULATION STRUCTURE OF THE PRIMARY MALARIA VECTOR IN SOUTH AMERICA, *ANOPHELES DARLINGI*, USING ISOZYME, RANDOM AMPLIFIED POLYMORPHIC DNA, INTERNAL TRANSCRIBED SPACER 2, AND MORPHOLOGIC MARKERS

SYLVIE MANGUIN, RICHARD C. WILKERSON, JAN E. CONN, YASMIN RUBIO-PALIS, JAMES A. DANOFF-BURG, AND DONALD R. ROBERTS

Department of Preventive Medicine and Biometrics, Uniformed Services University of the Health Sciences, Bethesda, Maryland; Department of Entomology, Walter Reed Army Institute of Research, Washington, District of Columbia; Department of Biology, University of Vermont, Burlington, Vermont; Division de Investigaciones, Escuela de Malariología y Saneamiento Ambiental, Maracay, Venezuela

**Abstract.** A genetic and morphologic survey of *Anopheles darlingi* populations collected from seven countries in Central and South America was performed to clarify the taxonomic status of this major malaria vector species in the Americas. Population genetics was based on three techniques including isozyme, random amplified polymorphic DNA-polymerase chain reaction (RAPD-PCR), and internal transcribed spacer 2 (ITS2) markers. The results of the isozyme analysis indicated moderate differences in the allele frequencies of three putative loci (glutamate oxaloacetate transaminase-1, isocitrate dehydrogenase-1, and phosphoglucosmutase) of the 31 analyzed. No fixed electromorphic differences separated the populations of *An. darlingi*, which showed little genetic divergence (Nei distances = 0.976-0.995). Fragments produced by RAPD-PCR demonstrated evidence of geographic partitioning and showed that all populations were separated by small genetic distances as measured with the 1 - S distance matrix. The ITS2 sequences for all samples were identical except for four individuals from Belize that differed by a three-base deletion (CCC). The morphologic study demonstrated that the Euclidean distances ranged from 0.02 to 0.14, with the highest value observed between populations from Belize and Bolivia. Based on these analyses, all the *An. darlingi* populations examined demonstrated a genetic similarity that is consistent with the existence of a single species and suggest that gene flow is occurring throughout the species' geographic range.

*Anopheles (Nyssorhynchus) darlingi* Root 1926 is the most efficient malaria vector in the New World.<sup>1</sup> In South America, its distribution stretches from Colombia to north-eastern Argentina. In Mexico, it is found as far north as Tabasco and Chiapas States, and in Central America, it occurs in Belize, Guatemala, Honduras, and occasionally in El Salvador.<sup>2</sup> However, this species has never been officially reported from Nicaragua, Costa Rica, or Panama, resulting in an apparent discontinuity in its distribution between Central and South America.<sup>3</sup>

Transmission of human malaria by *An. darlingi* occurs mainly in warm and humid forests along rivers in lowland areas (less than 550 meters above sea level), sometimes in coastal and piedmont ecoregions with high rainfall and tropical forests.<sup>4</sup> *Anopheles darlingi* is a very serious malaria vector throughout its geographic range because of its association with humans and its high rates of infection with the malaria parasites *Plasmodium falciparum*, *P. vivax*, and *P. malariae*.<sup>5</sup> It is the most anthropophilic and endophagic anopheline in the Americas, factors that obviously account for much of its potency as a major malaria vector.<sup>5-8</sup> As a result of complex sociologic, economic, and biologic factors, malaria has resurged in Brazil.<sup>9</sup> *Anopheles darlingi* is the primary vector of human malaria in the Amazon Basin,<sup>7</sup> and is the major contributor to the present resurgence of disease in South and Central America.

*Anopheles darlingi* was first described by Root<sup>10</sup> in 1926 from Rio de Janeiro in Brazil. In 1937, from samples collected near São Paulo (Brazil), Galvão and others<sup>11</sup> described a variety of *An. darlingi* named *pauлистensis* based on adult and egg characteristics. The latter characters seem to be at least quite variable in Brazil<sup>12,13</sup> and Venezuela.<sup>14</sup> Studies on the biology of *An. darlingi* also showed considerable varia-

tion in Brazil,<sup>8,15-19</sup> Suriname,<sup>20,21</sup> French Guiana,<sup>22</sup> Guyana,<sup>23</sup> Colombia,<sup>24</sup> and Venezuela.<sup>25</sup> In addition, variation has been described in its morphology,<sup>26,27</sup> chromosomes,<sup>28,29</sup> and isozymes.<sup>18,30-32</sup> Some of these reports have suggested that *An. darlingi* may be a species complex.<sup>19,30</sup>

In 1988, Linthicum<sup>3</sup> asserted that populations of *An. darlingi* collected throughout its geographic range showed little interpopulation variation among the diagnostic morphologic characteristics. Therefore, *An. darlingi* was defined as a monotypic subgroup and placed in the *Argyritarsis* section. However, a recent phylogenetic analysis (Danoff-Burg JA, Conn JE, unpublished data) using morphologic and molecular data suggested that the *Argyritarsis* section is paraphyletic with respect to the *Albimanus* section and *An. darlingi* has been placed in a basal grade in the *Nyssorhynchus* subgenus (Figure 1).

In spite of these reports, few comparative studies of *An. darlingi* populations have been undertaken. The present study was based on populations of *An. darlingi* from throughout much of its geographic range in Central America and South America (Figure 2). In Brazil, *An. darlingi* was collected in different states (Table 1), including the type-locality of the variant *pauлистensis* (from São Paulo State).

The approach we took to evaluate the taxonomic status of *An. darlingi* was based on morphometric and genetic analyses using isozyme, random amplified polymorphic DNA-polymerase chain reaction (RAPD-PCR), and internal transcribed spacer 2 (ITS2) markers. These genetic techniques have proven to be excellent for distinguishing species of insects<sup>33-41</sup> that otherwise are very difficult to separate on the basis of morphologic features. Our main objectives included 1) analysis of the differentiation and variability of *An. darlingi*, 2) comparison of *An. darlingi* populations with



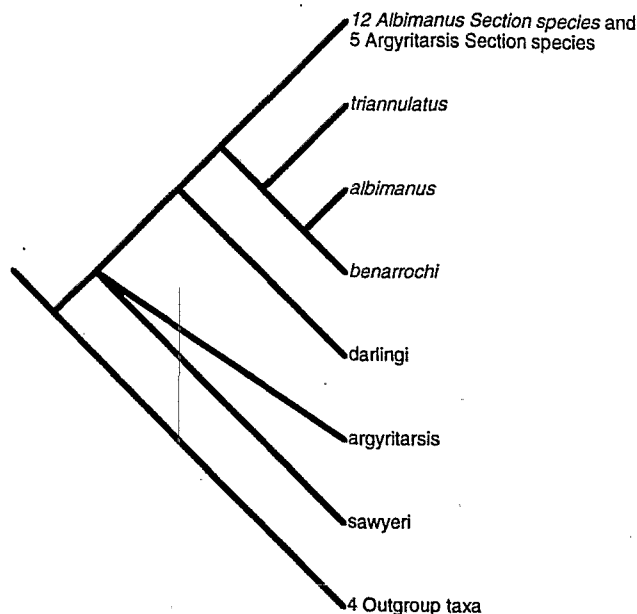


FIGURE 1. Basal portion of *Nyssorhynchus* subgenus phylogeny based on data from complete sequences of NADH dehydrogenase subunit 2, NADH dehydrogenase subunit 6, cytochrome oxidase subunit I, and internal transcribed spacer 2, as well as egg, larval, pupal, and adult morphologic characteristics.<sup>32</sup> Species in italics are those that were postulated to be in the *Albimanus* section, whereas those in roman font were said to be in the *Argyritarsis* section.<sup>3,26,70</sup> Relationships among the terminal species in the subgenus were simplified to demonstrate the basal placement of *Anopheles darlingi*.

the variant *paulistensis* described in the literature, and 3) comparison of the morphologic and genetic profiles of *An. darlingi* populations with other *Anopheles* species used as outgroups.

#### MATERIALS AND METHODS

**Mosquito populations.** From 1990 to 1996, we collected samples of *An. darlingi* from seven countries including Belize in Central America, and Bolivia, Brazil, Colombia, French Guiana, Peru, and Venezuela in South America (Figure 2 and Table 1). The countries were chosen to provide a spatial representation of the geographic distribution of this species and to examine samples from the type-locality of the variant *paulistensis*. Populations (Per 1–5) from Peru (Iquitos, 3°46'S, 73°15'W) were used only for the RAPD-PCR. In the morphologic study, populations of *An. darlingi* from northern Colombia (Beté, Departamento del Chocó, 5°45'N, 77°W) were also analyzed.

Samples used were primarily single individuals from isofemale progeny broods, wild-caught adults, and occasionally larvae or pupae reared individually to the adult stage. For the latter, fourth instar larval and/or pupal exuviae were preserved and each specimen was recorded, identified to species, and kept frozen at -70°C.

Other *Anopheles* species were included in the isozyme, RAPD-PCR, and morphologic analyses as outgroup taxa. We used *An. (Nys.) argyritarsis* Robineau-Desvoidy and *An. (An.) pseudopunctipennis* Theobald for the isozyme analysis, *An. (Nys.) nuneztovari* Gabaldon for the RAPD-PCR, and



FIGURE 2. Collecting areas of *Anopheles darlingi* in seven countries throughout the geographic distribution of this species. Each symbol (squares and circles) corresponds to a collection of multiple samples. Dark squares are samples used in genetic analyses, white squares in morphologic studies, and dark circles in both genetic and morphologic studies. ALB = Fortuna de Albarical (Amazonas, Venezuela); ARA = Araraquara (São Paulo, Brazil); ARI = Aripao (Bolívar, Venezuela); BAH = Itabela (Bahia, Brazil); BAR = Pereira Barreto (São Paulo, Brazil); BEL and BHZ = Belize (Central America); BEM = Belem (Pará, Brazil); BOL = Beni (Bolívia); CAP = Capanema (Pará, Brazil); CAS = Caicara (Bolívar, Venezuela); CMB = Costa Marques (Rondonia, Brazil); COL = Beté (Chocó, Colombia); CUI = San Antonio de Leverger (Mato Grosso, Brazil); DOU = Rio Jacare Pepira (São Paulo, Brazil); ELJ = El Juval (Trujillo, Venezuela); IQ = Iquitos (Peru); ITU = Ituxi River (Amazonas, Brazil); MAN = Manaus (Amazonas, Brazil); MAR = Maripasoula (French Guiana); MG = Mato Grosso (Brazil); OCA = Ocamo (Amazonas, Venezuela); PEX = Peixoto de Azevedo (Mato Grosso, Brazil); PIN = El Pinal (Bolívar, Venezuela); PR = Velha Timboteua (Pará, Brazil); SJM = San Juan de Manapiare (Amazonas, Venezuela); TRP = Trou-Poisson (French Guiana); URU = Uru-curí (Pará, Brazil); YUC = La Yuca (Bolívar, Venezuela).

four species in the *Nyssorhynchus* subgenus: *An. albitarsis* Lynch Arribalzaga, *An. argyritarsis*, *An. braziliensis* (Chagas'), and *An. marajoara* (Galvão and Damasceno) for the morphologic analysis. When relationships among 21 other *Nyssorhynchus* taxa were reconstructed using only ITS2, *An. darlingi* was monophyletic and included in a basal unresolved polytomy. Therefore, no outgroups were used in the present study.

**Isozyme electrophoresis.** Isozymes were separated by horizontal starch gel electrophoresis. Experimental procedures are detailed in the publication by Manguin and others.<sup>42</sup> A total of 35 enzyme systems was screened on two different buffers: the morpholine buffer system<sup>43</sup> (Morph, pH 6.1), and the Tris-citrate buffer system<sup>44</sup> (TCss, pH 6.7). Of the 35 enzyme systems tested, 23 showed good allelic resolution, including 31 putative loci (Table 2). For each locus, the most frequent electromorph was designated the 100 allele and all other alleles were measured relative to it. Electromorph genotype frequencies were used as input for BIOSYS-1.<sup>45</sup> Analysis of each population included computation of allele frequencies, heterozygosity per locus, additional

TABLE 1  
Geographic information on the sample sites of *Anopheles darlingi*

Country	State	Locality and collection no.	Longitude/latitude	Collection code for each technique, <sup>1,2,3,4,5</sup>
Belize	Cayo	Sibun River	17°07'–18°N/88°34'–40'W	BHZ <sup>1,3</sup> (542, 556–9, 565, 571–3, 578–82, 615), Bel <sup>2</sup> 1–10, BEL <sup>4</sup>
	Cayo	5 Blues Lake, Novelo	17°08'–09°N/88°36'–38'W	BHZ <sup>1</sup> (548–9, 567, 611), BHZ <sup>1</sup> (563, 612)
	Cayo	Churchyard	17°18'N/88°34'W	BHZ <sup>1</sup> (584–5, 604)
Bolivia	Beni	Guayaramerin	10°51'S/65°21'W	BOL: GU, <sup>1,4,5</sup> BOL <sup>2</sup> (1–4)
	Beni	Riberalta, San Ramon	11°02'S/66°04'W	BOL: SR <sup>1,5</sup> , BOL <sup>2</sup> (5–8, 10–17, 19–22)
	Beni	Riberalta, Antofagasta	12°56'S/64°30'W	BOL: Ant, <sup>1,5</sup> BOL <sup>2</sup> (9,18)
Brazil	Amazonas	Manaus	03°08'S/60°01'W	Man <sup>2</sup> (1–5), MAN <sup>5</sup>
	Amazonas	Ituxi River: Floresta, Labrea, Estirao	7°59'–8°01'S/65°14'–16'W	ITU <sup>1,3</sup> : BR (5, 10), BR (2), BR (7)
	Amazonas	Ituxi River: Ilha do Jucia	7°47'S/65°07'W	ITU <sup>1</sup> : BR (13)
	Bahia	Itabela	16°34'S/39°24'W	BAH: Bah <sup>2</sup> (1–5)
	Mato Grosso	Peixoto de Azevedo	10°23'S/54°54'W	PEX: BR <sup>1,5</sup> (544, 546, 020, 701), Pex <sup>2</sup> (1–28)
	Mato Grosso	Mato Grosso	15°00'S/59°55'W	MG <sup>4</sup>
	Mato Grosso	Santo Antonio de Leverger	15°51'S/56°03'W	Cui <sup>2</sup>
	Para	Capanema, Velha Timboteua, Urucuri	01°00'–12'S/47°11'–18'W	Cap <sup>2</sup> (1–8), PR, <sup>4,5</sup> CAP <sup>5</sup> , URU <sup>5</sup>
	Para	Belem, Embrapa	01°25'S/48°77'W	Bem <sup>2</sup> (1, 2)
	Rondonia	Costa Marques	12°26'S/64°13'W	CMB <sup>4</sup>
	São Paulo	Pereira Barreto	20°46'S/51°09'W	BAR: BR <sup>1,3</sup> (21, 23, 25, 26, 27), Igu <sup>2</sup> (1, 2)
	São Paulo	Araraquara	22°05'S/48°26'W	ARA <sup>1</sup> : BR (28, 29)
	São Paulo	Rio Jacare Pepira (near Dourado)	22°07'S/48°18'W	Dou <sup>2</sup> (1–20)
French Guiana	Itacoubou	Trou-Poisson	5°26'N/53°05'W	TRP: FG <sup>1,3,4</sup> (1,3 14); FRG <sup>2</sup> (1–5)
	Maripasoula	Maripasoula	3°38'N/54°03'W	MAR <sup>1,4</sup>
Venezuela	Amazonas	Fortuna de Albarical, Puerto Ayacucho	05°58'–59'N/67°25'–76°39'W	ALB, <sup>1,4,5</sup> Ven <sup>2</sup> (2, 4–12)
	Amazonas	San Juan de Manapiare	5°22'N/66°05'W	SJM <sup>4</sup>
	Amazonas	Ocamo	2°50'N/65°14'W	OCA <sup>4</sup>
	Bolivar	Aripao	7°20'N/65°10'W	ARI <sup>4</sup>
	Bolivar	Corobal, La Yuca	7°48'–51'N/65°40'–42'W	YUC <sup>1,4</sup> : COR, VZ (9, 10)
	Bolivar	Caicara	7°49'N/66°12'W	CAS <sup>4</sup>
	Bolivar	El Pinal	6°30'N/61°40'W	PIN <sup>4</sup>
	Trujillo	El Juval	9°33'N/70°39'W	ELJ, <sup>1,5</sup> Ven <sup>2</sup> (1,3)

\* <sup>1</sup> = isozymes; <sup>2</sup> = random amplified polymorphic DNA–polymerase chain reaction; <sup>3</sup> = internal transcribed spacer 2 (ITS2); <sup>4</sup> = morphology; <sup>5</sup> = ITS2 (Danoff-Burg JA, Conn JE, unpublished data). For definitions of abbreviations, see Figure 2.

TABLE 2  
Electrophoretically detected enzyme systems of *Anopheles darlingi*

Enzyme system	E.C. number*	Symbol	No. of loci†	Buffer‡
1. Adenylate kinase	2.7.4.3	AK	1	Morph
2. Aldehyde oxidase	1.2.3.1	AO	1	Morph
3. Arginine kinase	2.7.3.3	ARGK	1	TCss
4. Esterase	3.1.1.1	EST	2	Morph
5. Fumarase	4.2.1.2	FUM	1	TCss
6. Glycerol dehydrogenase	1.1.1.72	GCD	1	Morph
7. Glutamate oxaloacetate transaminase	2.6.1.1	GOT	2	Morph
8. $\alpha$ -Glycerophosphate dehydrogenase	1.1.1.8	GPDH	1	Morph
9. Glyceraldehyde-3-phosphate dehydrogenase	1.2.1.12	G3PDH	1	Morph
10. Glutathione reductase	1.6.4.2	GR	2	TCss
11. $\beta$ -Hydroxyacid dehydrogenase	1.1.1.30	HAD	1	Morph
12. Hexokinase	2.7.1.1	HK	2	Morph
13. Isocitrate dehydrogenase	1.1.1.42	IDH	2	TCss
14. Leucine amino peptidase	3.4.11.1	LAP	2	TCss
15. Malate dehydrogenase	1.1.1.37	MDH	2	Morph
16. Malic enzyme	1.1.1.40	ME	1	Morph
17. Mannose-6-phosphate isomerase	5.3.1.8	MPI	1	Morph
18. 6-Phosphogluconate dehydrogenase	1.1.1.44	6PGD	1	Morph
19. Phosphoglucose isomerase	5.3.1.9	PGI	1	TCss
20. Phosphoglucomutase	5.4.2.2	PGM	1	Morph
21. Pyruvate kinase	2.7.1.40	PK	2	Morph
22. Triose phosphate isomerase	5.3.1.1	TPI	1	TCss
23. Xanthine dehydrogenase	1.2.1.37	XDH	1	TCss
Total			31	

\* Enzyme commission number.

† Number of scorable bands per phenotype.

‡ Refers to electrophoresis buffer: Morph = morpholine; TCss = Tris-citrate.

measures of genetic variability, and a test for conformance to Hardy-Weinberg equilibrium at single loci by chi-square analysis. Differentiation among the populations was measured by F-statistics. Nei's<sup>46</sup> unbiased genetic distances and identities and Rogers<sup>47</sup> genetic distances were clustered by the unweighted pair group method using arithmetic average (UPGMA) to produce the phenogram.

**Random amplified polymorphic DNA-polymerase chain reaction.** Experimental procedures can be found in the publications by Wilkerson and others.<sup>34,35,48</sup> Sixty decamer primers (Operon sets A, B, C; Operon Technologies, Alameda, CA) were screened using three individuals from a single family of *An. darlingi* from Peixoto de Azevedo (Brazil). From these, a subset of eight primers that produced consistent bands that could be scored in each of the three specimens was chosen to analyze the entire sample of 124 individuals from 13 populations (Table 1). Five of the eight gave consistent results for all specimens in the study. In contrast, 13 individuals of *An. nuneztovari* from two populations were analyzed using the same five primers. *Anopheles nuneztovari* is placed in a sister clade to the one including *An. darlingi*. The resultant data set was formatted as described by Black<sup>49</sup> and a 1 - S distance matrix was generated using the similarity option in the RAPDLOT (FORTRAN programs for the analysis of RAPD-PCR markers in populations; Black IV, WC, Colorado State University, Fort Collins, CO) program. The formula is derived from the Nei and Li<sup>50</sup> similarity index:  $S = 2N_{AB}/(N_A + N_B)$  where  $N_{AB}$  are the fragments that two individuals share in common and  $N_A$  and  $N_B$  are the number of fragments in individuals A and B, respectively. The matrix was analyzed in PHYLIP 3.5C (Phylogeny inference package; Felsenstein J, University of Washington, Seattle, WA) using the NEIGHBOR program

with the UPGMA option and a phenogram was produced with DRAWGRAM, also in PHYLIP 3.5C. RAPDBOOT<sup>51</sup> was used to generate 100 pseudoreplicate distance matrices, which were collapsed to form 100 trees with UPGMA. The bootstrap consensus tree was derived from the 100 UPGMA trees with the CONSENSUS program in PHYLIP 3.5C.

**Sequencing of ITS2.** Total DNA was extracted from specimens using the extraction technique of Collins and others.<sup>52</sup> The PCR temperature profile consisted of 37 cycles of 1 min at 95°C, 1 min at 45°C, and 1.5 min at 72°C. Primers specific for the ITS2 region<sup>53</sup> annealed to the conserved regions of the 5.8S and 28S ribosomal subunits that flank this region. All 13 specimens were manually sequenced and representatives from each of the 12 sites were resequenced using an ABI 373 automated sequencer using the ABI PRISM Dye terminator cycle sequencing kit (Perkin Elmer, Norwalk, CT). Contig assembly and related sequence analysis was performed using Sequencher 3.0 (Gene Codes Corp., Ann Arbor, MI). The GenBank accession number of the ITS2 for *An. darlingi* populations from South America is U92337, and the number for populations from Belize is AF051274 (Danoff-Burg JA, Conn JE, unpublished data).

**Morphology.** Selected wing, leg, and head characteristics were measured and analyzed on 305 adult females of *An. darlingi* from 17 populations (Figure 2 and Table 1) using a dissecting microscope. The head characteristic was the length of the proboscis and those of the wings and legs are illustrated in Figure 3A and B, respectively. The morphologic terms and abbreviations used in this figure follow those of Harbach and Knight,<sup>54,55</sup> Wilkerson and Peyton,<sup>56</sup> and Peyton (unpublished data). The Program Statistica<sup>57</sup> was used for statistical analysis among populations with  $N \geq 10$ . To measure the closeness of *An. darlingi* populations based on

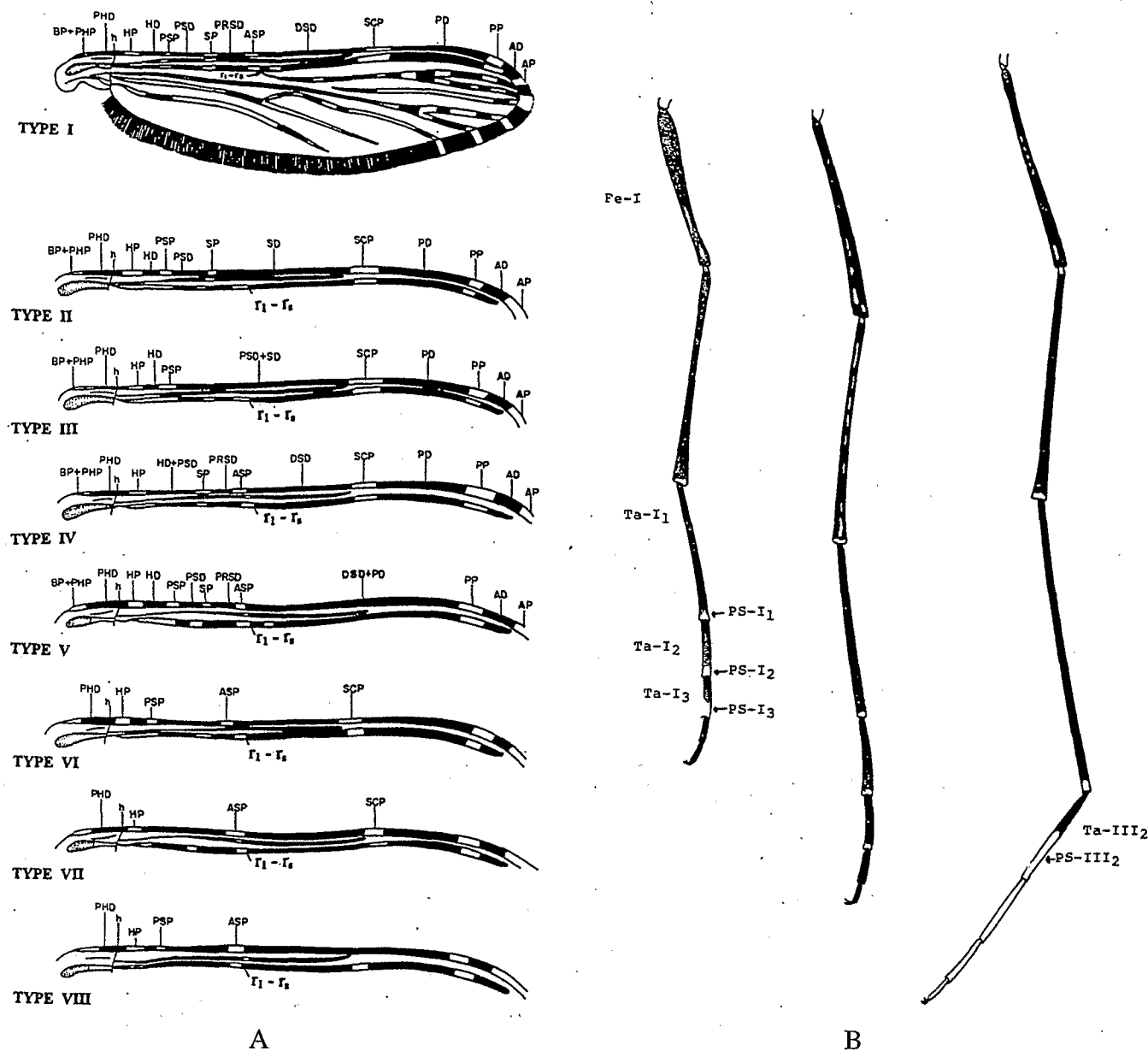


FIGURE 3. Morphologic wing and leg characteristics of *Anopheles darlingi*. A, wing types based on patterns of dark and pale spots on the costa. BP + PHP = basal pale + prehumeral pale; PHD = prehumeral dark; h = humeral crossvein; HP = humeral pale; HD = humeral dark; PSP = presector pale; PSD = presector dark; SP = sector pale; SD = sector dark; PRSD = proximal sector dark; ASP = accessory sector pale; DSD = distal sector dark; SCP = subcostal pale; PD = preapical dark; PP = preapical pale; AD = apical dark; AP = apical pale (wing spot);  $r_1 - r_2$  = radius one and cell minus radial sector. B, legs showing the characteristics measured. Fe-I = forefemur; Ta-I<sub>1</sub> = foretarsomere 1; pale spot (PS-I<sub>1</sub>) on Ta-I<sub>1</sub>; Ta-I<sub>2</sub> = foretarsomere 2; pale spot (PS-I<sub>2</sub>) on Ta-I<sub>2</sub>; Ta-I<sub>3</sub> = foretarsomere 3; pale spot (PS-I<sub>3</sub>) on Ta-I<sub>3</sub>; Ta-III<sub>2</sub> = hindtarsomere 2; pale spot (PS-III<sub>2</sub>) on Ta-III<sub>2</sub>.

linear continuous characteristics such as morphologic ones, the Euclidean distances among populations were estimated by cluster analysis.<sup>58</sup>

#### RESULTS

**Isozyme analysis.** An isozyme comparison of 31 loci (Table 2) among the populations of *An. darlingi* indicated that mean heterozygosity ranged from 0.063 to 0.122 (Table 3) with a mean  $\pm$  SE of  $0.1 \pm 0.023$  across all populations.

The F-statistic ( $F_{ST}$ ), a measure of the amount of differ-

entiation among subpopulations, showed a low mean value of 0.102 and the mean index of fixation of individuals relative to the total of subpopulations ( $F_{IS}$ ) had a moderate mean value of 0.039. Three  $F_{ST}$  values with moderate differentiation, were found for glutamate oxaloacetate transaminase-1 (*Got-1*) (0.170), isocitrate dehydrogenase-1 (*Idh-1*) (0.170), and phosphoglucosmutase (*Pgm*) (0.204).

There were five different alleles for *Got-1*. Populations of *An. darlingi* from São Paulo (Brazil) had a 62% frequency for allele 100 and 37% for allele 85, whereas all the other populations had a frequency more than 80% for allele 100.

TABLE 3  
Measures of genetic variability of *Anopheles darlingi* (1–7), *An. pseudopunctipennis* (8), and *An. argyritarsis* (9)\*

Populations	No. of samples	Mean sample size/locus	Mean no. of alleles/locus	% Polymorphic loci†	Mean heterozygosity	
					Direct-count	HdyWbg expected‡
1. Belize	4	109.4 (1.2)	2.0 (0.2)	16.1	0.063 (0.020)	0.065 (0.020)
2. Amazonas, Brazil	4	99.6 (1.2)	2.5 (0.2)	45.2	0.101 (0.018)	0.104 (0.019)
3. São Paulo, Brazil	3	93.4 (1.2)	2.6 (0.2)	48.4	0.122 (0.023)	0.130 (0.025)
4. Mato Grosso, Brazil	1	18.0 (0.0)	1.9 (0.2)	48.4	0.122 (0.029)	0.128 (0.029)
5. Venezuela	3	104.7 (0.9)	2.7 (0.2)	35.5	0.098 (0.024)	0.102 (0.024)
6. French-Guiana	2	93.5 (0.6)	2.4 (0.2)	19.4	0.079 (0.021)	0.084 (0.023)
7. Bolivia	3	23.2 (0.5)	2.0 (0.2)	45.2	0.117 (0.025)	0.125 (0.026)
8. <i>An. pseudopunctipennis</i>	1	5.8 (0.1)	1.3 (0.1)	29.0	0.081 (0.028)	0.088 (0.029)
9. <i>An. argyritarsis</i>	1	6.0 (0.0)	1.2 (0.1)	19.4	0.048 (0.025)	0.051 (0.021)

\* Values in parentheses are standard errors.

† A locus is considered polymorphic if the frequency of the most common allele does not exceed 0.99.

‡ Unbiased estimate. HdyWbg = Hardy-Weinberg equilibrium.

(Table 4). In the case of *Idh-1*, which has four alleles, all populations displayed a frequency greater than 72% for allele 100, except the ones from Belize, which had a 40% frequency for allele 100 and 59% for allele 86. The third locus is *Pgm*, which had five alleles. The Venezuelan populations had a frequency of 70% for allele 80 and 28% for allele 100, whereas all the other populations had a frequency greater than 69% for allele 100.

Regardless of the allele frequency differences, Nei's index of genetic identity (above the diagonal) indicated a high degree of similarity among all populations, with values greater than 0.975 (Table 5). The phenogram illustrated that *An. darlingi* populations from Brazil and Bolivia had high genetic identities (> 0.99). Then, by decreasing order of similarity, populations from French Guiana, Belize, and finally Venezuela followed with a genetic identity of 0.981 (Figure 4A).

The comparison of *An. darlingi* populations with two other anopheline species showed that with *An. (Nys.) argyritarsis*, the genetic distance was 0.331, and with *An. (An.) pseudopunctipennis*, the genetic identity was 0.149 (Figure 4B). This comparison emphasizes the genetic homogeneity found within the *An. darlingi* populations studied. The population of the variant *paulistensis* presented no significant differences compared with the other *An. darlingi* populations.

**Random amplified polymorphic DNA-polymerase chain reaction.** The five primers used in this study produced 35 bands that could be scored in *An. darlingi* and 17 in *An. nuneztovari*, including four shared bands. These bands ranged in size from 0.350 to 2.323 kilobasepairs (Table 6). All individuals of *An. darlingi* clustered together, as did all *An. nuneztovari*, each with 100% bootstrap support (Figure 5). Within both species, there was some evidence of geographic partitioning of most populations. Samples of *An. darlingi* were partitioned into four main clusters (Figure 5). Cluster I comprises most (23 of 28) of the Peixoto de Azevedo individuals (central Brazil); Cluster II includes samples

from Bolivia, many parts of Brazil, French Guiana, and Venezuela; Cluster III contains many (16 of 20) of the Rio Jacare Pepira individuals (southern Brazil); and Cluster IV contains most (9 of 10) of the Belize specimens. Genetic distances separating all clusters of *An. darlingi* were small in comparison with those separating the two clusters of *An. nuneztovari*, which included samples from central Brazil (Peixoto de Azevedo) and northeastern Brazil (Belem).

**Sequencing of ITS2.** Based on the characterization of the ITS2 region of *An. darlingi*, no variation was observed among the 406 basepairs of the ITS2 region of the nine individuals that were sequenced in the present study from South America, including Brazil (Ituxi River and Pereira Barreto) and French Guiana (Trou-Poisson and Maripasoula). However, the four individuals from Belize all had an identical small deletion of CCC (Figure 6). The three base-pair differences between populations from Belize and South America represents a value of 0.74% intraspecific variation in the ITS2. When relationships among the taxa were reconstructed using only ITS2, the *An. darlingi* populations from South America and Belize were a monophyletic taxon that was not allied with any other species and included in a basal unresolved polytomy.

**Morphology.** The morphologic study showed wide variation in the pattern of pale and dark spots on wing costa, making it possible to differentiate eight classes of wing patterns (Figure 3A). Costal spots are characteristic for the subgenus *Nyssorhynchus*,<sup>56</sup> in which the basal dark spot (BD) is absent and the basal pale (BP) and prehumeral pale (PHP) are fused (BP plus PHP). In Type I, the accessory sector pale (ASP) is present and divides the sector dark (SD) into proximal sector dark (PRSD) and distal sector dark (DSD);<sup>59</sup> in Type II, the absence of the ASP resulted in the fusion of the PRSD and DSD, which become the SD; in Type III, the SP and ASP are absent; in Type IV, the presector pale (PSP) is absent; in Type V, the subcostal pale (SCP) is absent; thus, the DSD and PD are fused; in Type VI, the SP is absent; in

TABLE 4  
Relative allele frequencies for three loci of *Anopheles darlingi*\*

Locus†	Allele‡	Brazil						
		Belize	Amazonas	São Paulo	Mato Grosso	Venezuela	French Guiana	Bolivia
<i>Got-1</i>	n	114	103	99	18	107	95	24
	117	—	—	—	—	0.009	—	—
	112	—	—	0.01	0.056	0.023	0.021	—
	100	<b>0.982</b>	<b>0.981</b>	<b>0.616</b>	<b>0.944</b>	<b>0.808</b>	<b>0.968</b>	<b>0.958</b>
	85	0.018	0.015	<b>0.374</b>	—	0.056	—	0.042
	70	—	0.005	—	—	0.103	0.011	—
<i>Idh-1</i>	(H)	0.035	0.039	0.343	0.111	0.346	0.063	0.083
	n	102	102	99	18	107	95	24
	115	0.02	0.029	0.056	0.111	0.084	0.137	0.042
	100	0.392	<b>0.936</b>	<b>0.889</b>	<b>0.722</b>	<b>0.752</b>	<b>0.805</b>	<b>0.896</b>
	86	<b>0.588</b>	0.034	0.051	0.167	0.164	0.058	0.063
	72	—	—	0.005	—	—	—	—
<i>Pgm</i>	(H)	0.52	0.127	0.222	0.556	0.439	0.326	0.208
	n	111	105	101	18	108	97	24
	120	—	—	0.005	0.028	—	—	0.021
	115	—	0.095	0.089	0.083	0.009	0.026	0.167
	100	<b>0.797</b>	<b>0.719</b>	<b>0.851</b>	<b>0.694</b>	<b>0.282</b>	<b>0.964</b>	<b>0.729</b>
	80	0.203	0.181	0.05	0.194	<b>0.704</b>	0.01	0.083
	64	—	0.005	0.005	—	0.005	—	—
	(H)	0.315	0.343	0.277	0.5	0.426	0.072	0.458

\* Dashes represent 0; bold numbers represent the allele frequencies discussed in the Results.

† *Got-1* = glutamate oxaloacetate transaminase; *Idh-1* = isocitrate dehydrogenase; *Pgm* = phosphoglucumutase.

‡ n = number of specimens; h = heterozygosity (direct-count) per locus.

Type VII, the PSP and SP are absent; and in type VIII, the SP and SCP are absent.

The observed frequency distribution of wing types in the different populations analyzed varied significantly and are population dependent ( $\chi^2 = 161.34$ ,  $P = 0.0016$ ). In general, Type I was the most frequent type of wing followed by Type VI. In the Belize population, only Type I and II were present, while Type II was absent from the populations of French Guiana, Brazil, and Bolivia. The Venezuela populations of Caicara and Albarical showed up to six different types of wings.

Analysis of variance (ANOVA) of the proportions of the length of each costal wing spot divided by the length of the wing for the 13 populations showed that the proportion pre-humeral dark/humeral pale (PHD/HP) (Figure 3A) is a valid diagnostic characteristic for *An. darlingi* ( $F = 78.1361$ ,  $P = 0.000001$ ) and can be used as a marker to differentiate this species from other morphologically similar ones such as *An. marajoara*, *An. braziliensis*, *An. argyritarsis*, and *An. albittarsis*.

The highest Euclidean distance (ED) was observed be-

tween the Belize and Bolivia populations (0.14). The Bolivian population is separated from the others by a distance of 0.08. The Brazil populations of Costa Marques and Pereira Barreto are similar to each other ( $ED = 0.04$ ) and to the Venezuela populations. The population from Colombia located west of the Andes Mountains is very close ( $ED = 0.02$ ) to the population of San Juan de Manapiare, located in the Venezuelan Amazon, east of the Andes (Figure 2).

Analysis of the morphology of the proboscis and legs resulted in valid diagnostic characteristics that could separate *An. darlingi* populations such as proboscis (P) and forefemur (P/Fe-I), pale spot on foretarsomere (PS-I<sub>1</sub>/Ta-I<sub>1</sub>, PS-I<sub>2</sub>/Ta-I<sub>2</sub>, PS-I<sub>3</sub>/Ta-I<sub>3</sub>) and on hindtarsomere (PS-III<sub>2</sub>/Ta-III<sub>2</sub>) (Figure 3B). Galvão and others<sup>11</sup> pointed out that the variant *paulistensis* had more dark scales on the hindtarsomere 2 than the *An. darlingi* described by Root. Nevertheless, for this characteristic, we found that the Pereira Barreto population (*paulistensis* type locality) was similar to the Bolivian population. The ANOVA of these proportions for *An. darlingi*, *An. marajoara*, *An. braziliensis*, *An. argyritarsis*, and *An. albittarsis* was significantly different ( $P < 0.0001$ ), and the best

TABLE 5  
Matrix of genetic distance of *Anopheles darlingi* (1–7), *An. pseudopunctipennis* (8) and *An. argyritarsis* (9)\*

Population	1	2	3	4	5	6	7	8	9
1. Belize	****	0.987	0.978	0.988	0.983	0.985	0.980	0.114	0.307
2. Amazonas, Brazil	0.014	****	0.992	0.995	0.987	0.992	0.993	0.134	0.334
3. São Paulo, Brazil	0.022	0.008	****	0.990	0.976	0.984	0.992	0.131	0.341
4. Mato Grosso, Brazil	0.012	0.005	0.010	****	0.986	0.988	0.991	0.125	0.337
5. Venezuela	0.017	0.013	0.024	0.014	****	0.979	0.979	0.124	0.322
6. French Guiana	0.015	0.008	0.016	0.012	0.022	****	0.985	0.126	0.313
7. Bolivia	0.020	0.007	0.008	0.009	0.021	0.015	****	0.118	0.367
8. <i>An. aygyritarsis</i>	1.181	1.098	1.076	1.087	1.134	1.161	1.003	****	0.324
9. <i>An. pseudopunctipennis</i>	2.172	2.007	2.032	2.081	2.089	2.069	2.140	1.128	****

\* Values above the diagonal are Nei's unbiased<sup>24</sup> genetic identities; values below the diagonal are Nei's unbiased<sup>31</sup> genetic distances.

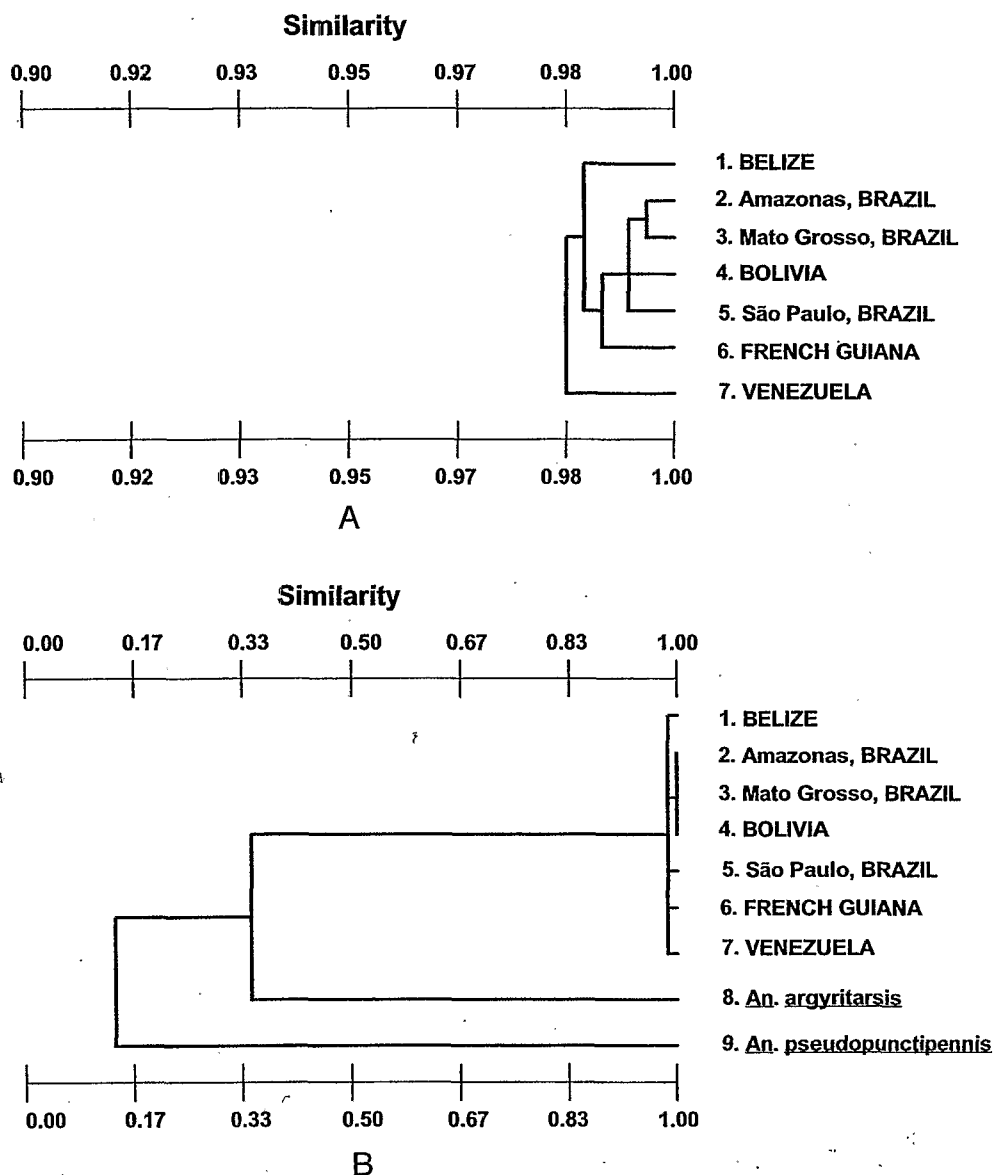


FIGURE 4. Unweighted phenogram from Nei's<sup>46</sup> unbiased genetic distance matrix. A, for all *Anopheles darlingi* populations (cophenetic correlation = 0.815). B, for all *An. darlingi* populations, *An. pseudopunctipennis*, and *An. argyritarsis* (cophenetic correlation = 0.983).

TABLE 6

Approximate sizes of random amplified polymorphic DNA (RAPD) fragments used in comparison of *Anopheles darlingi* populations and comparison of *An. darlingi* with *An. nuneztovari*

Primer	Size of RAPD fragments (kilobasepairs)*
B12	1.569, 1.501†, 1.226, 1.140, 1.135, 0.940, 0.911, 0.892†, 0.888, 0.861†, 0.705†, 0.675, 0.552, 0.439‡, 0.423†
A09	1.888, 1.593, 1.323‡*, 1.071, 0.872, 0.817†, 0.781, 0.449, 0.432‡, 0.350
B04	1.150‡, 0.760, 0.707, 0.468†, 0.429, 0.422†, 0.409, 0.358
A07	2.322†, 1.721†, 1.489, 1.297, 1.152, 1.045†, 0.976†, 0.790, 0.735, 0.636, 0.589, 0.509
C18	1.935‡, 1.252, 0.718

\* Occurrence of fragments: no annotation = *An. darlingi*.

† *An. nuneztovari*.

‡ Both species.

diagnostic characteristic to separate all four species is the proportion PS-III<sub>2</sub>/Ta-III<sub>2</sub>. This characteristic was previously used by Linthicum<sup>3</sup> to separate *An. albitarsis* and *An. marajoara* only.

#### DISCUSSION

Based on the isozyme analysis, the mean  $\pm$  SE heterozygosity of  $0.100 \pm 0.023$  for *An. darlingi* (index that reflects the genetic variability) was similar to the average value found in other Diptera ( $0.115 \pm 0.009$ ).<sup>60</sup> This species showed a higher genetic variability than the *An. pseudopunctipennis* populations ( $0.059 \pm 0.020$ ) studied by Mangin and others.<sup>42</sup> However, lower genetic variability was found for the Belize populations (0.063) compared with South American populations (0.079–0.122, with a mean  $\pm$  SE of  $0.107 \pm 0.017$ ). Belize and other countries of Central

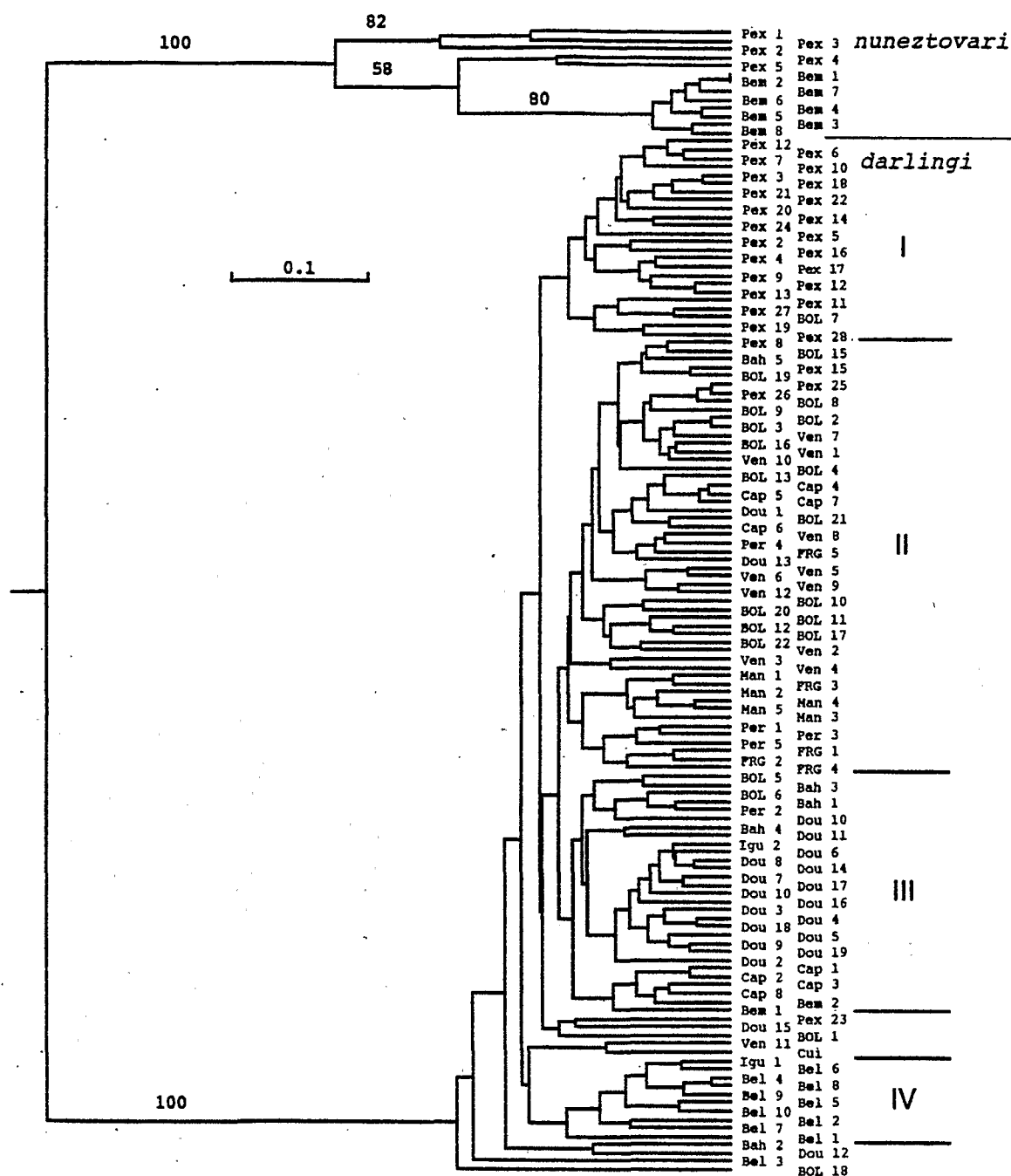


FIGURE 5. Phenogram showing relationships among 124 individuals of *Anopheles darlingi* and 13 *An. nuneztovari*. Branch lengths are proportional to 1 - S, and the scale bar is equal to 0.1. On selected branches, the bootstrap value of 100 repetitions is shown. The roman numerals indicate the four primary clusters.

America are part of a rather narrow and restricted land mass that is scored by many short, parallel river systems. As a consequence, populations of *An. darlingi* from Belize, and more globally from Central America, have a restricted distribution compared with the large land mass and extensive river systems occurring in South America. It may be that the loss of population heterozygosity in Belize reflects the normally expected loss of polymorphic alleles in populations that are confined to restricted and isolated environments. In other words, the gene flow of *An. darlingi* populations in

Central America occurs in a more reduced area than in South America, causing a bottleneck effect that resulted in less polymorphic populations. Our hypothesis is that a northern extension of populations from South America established *An. darlingi* populations in Central America. It may also be that the modern discontinuous geographic distribution of this species occurred secondarily to the original northward extension of *An. darlingi* populations.

Overall genetic identity within *An. darlingi* populations was high (0.976–0.995), and these identities are markedly

A. darlingi	SA	CAGTGCAGAG	TACACATTTT	TGAGTGCCCA	▼CATTCACCGC	AGAACCAACT	50
A. darlingi	BE	.....	.....	.....	.....	.....	50
A. darlingi	SA	AGCGAGGTCG	TGCCGCGGCC	GGTCAGCCGG	CCGGTTAGCT	GGCTACTGAT	100
A. darlingi	BE	.....	.....	.....	.....	.....	100
A. darlingi	SA	GATTTGATTG	ACGCGCCGCG	TCCCCAACCG	GACGCGCCCG	TGTGTGGTCA	150
A. darlingi	BE	.....	.....	.....	.....	.....	150
A. darlingi	SA	AGCATTGAAG	GACTGTGGCG	TGGTGGGTGC	ACCGTGTGTC	GTTGCTTAAT	200
A. darlingi	BE	.....	.....	.....	.....	.....	200
A. darlingi	SA	ACGCGACCCCT	CTCTCCGGTT	TCACATCTGG	AGCGGGCTAT	CCAGTCACAA	250
A. darlingi	BE	.....	.....	.....	.....	.....	250
A. darlingi	SA	TCCCCAGCGA	AATGTGCCGA	TACACGGGTA	GCCCCGATGT	GGAGATCCAA	300
A. darlingi	BE	.....	.....	.....	.....	.....	300
A. darlingi	SA	GCGAGGACCT	CCCTCAAAAC	CATTGTGATG	AAACCCACCC	ACACAAGAGA	350
A. darlingi	BE	.....	.....	.....	.....	.....	350
A. darlingi	SA	GAAGAGAGAG	AGCGACCAAA	AGCAACGTTC	GCACGCGCTG	TCAGCTCATC	400
A. darlingi	BE	.....	.....	.....	.....	.....	400
A. darlingi	SA	GAGCGCGCAC	ACGGATCTAG	GAAGTAGGAT	CTCAAGTGGG	▼CCTCAATATG	450
A. darlingi	BE	.....	.....	.....	.....	.....	450
A. darlingi	SA	TGTGACTACC	CCTA				500
A. darlingi	BE	.....	.....				500

FIGURE 6. Sequence of 34 nucleotides of the 5.8S region, the entire 406 nucleotides of the internal transcribed spacer 2 (ITS2) region, and 24 nucleotides of the 28S region for *Anopheles darlingi*. The arrowheads represent the first and last sequences of the ITS2 region. SA = South America; BE = Belize, which differs only by a small three-base deletion (CCC) at position 179-181. The sequence has been deposited in GenBank (accession number U92337).

higher than the value of 0.85, suggested by Avise<sup>61</sup> as the lower limit for conspecific populations. For instance, in other anopheline species, values ranged from 0.84 to 0.88 between both species, *An. gambiae* s.s. and *An. arabiensis*,<sup>62-64</sup> and from 0.92 to 1.0 among *An. pseudopunctipennis* populations.<sup>42</sup> In the study of Steiner and others,<sup>30</sup> an *An. darlingi* population from southern Brazil had values ranging between 0.592 and 0.772, suggesting the existence of more than one species. In comparison with another study,<sup>18</sup> genetic identity of southern and northern Brazil populations has been found to be much higher, with a value of 0.952 within the range of intrapopulation variation. Similarly, the range of our genetic identity values for all the Brazil populations was both narrower and higher (0.976-0.992) than the former one.

Although some moderate differentiation was found in three loci (*Got-1*, *Idh-1*, and *Pgm*), the mean  $F_{ST}$  values showed negligible differentiation among *An. darlingi* and no fixed differences were found. In addition, the moderate mean  $F_{IS}$ , with a value of 0.039, suggests that random mating among the populations of *An. darlingi* is occurring.<sup>65</sup> Comparison of the isozyme analysis between *An. darlingi* and *An. pseudopunctipennis*<sup>42</sup> showed a higher homogeneity among populations of the former species, with  $F_{ST}$  values of 0.102 and 0.375, and Nei genetic identities ranging between 0.976 and 0.995, and 0.924 and 1.0, respectively. In the case of *An. darlingi*, there were no clear groupings of populations as found for *An. pseudopunctipennis*.

Our RAPD-PCR results support the conclusion that the widespread sampled populations of *An. darlingi* are conspecific. In addition to high similarity values among the populations, comparisons with *An. nuneztovari* demonstrated the level of differentiation expected between species. Of the 35 markers used in this analysis, seven are monomorphic, i.e., occur in > 95% of the individuals tested, and two of these occur in all individuals. Wilkerson and others<sup>34,35</sup> found sim-

ilar numbers of correlated diagnostic markers in each of the four species of the *Albitarsis* complex (3-7) using the same 60 RAPD primers as in the present study.

Our analysis produced four large and three small clusters, indicative of geographic partitioning. Since *An. darlingi* clusters usually include individuals from widely separated populations, e.g., cluster III includes individuals from central and northern Brazil and Bolivia, the case can also be made that the level of mixis implied by the clustering would likely be sufficient to ensure panmixis (random mating).

Interestingly, the two clusters in the RAPD-PCR data for *An. nuneztovari* (Belém, northeastern Brazil and Peixoto, central Brazil) are similar to the distinctive mitochondrial DNA lineages of 12 *An. nuneztovari* populations in Belém and central Amazonian Brazil (Manaus and Boa Vista),<sup>66</sup> underscoring some congruence, in this case, between two different molecular markers.

Intraspecific variation in the ITS2 region of 21 members of the *Nyssorhynchus* subgenus varies from 0% to 2.8%. Therefore, the value of 0.74% for *An. darlingi* represents a low value for intraspecific variation of the subgenus. Most of this variation is in the form of insertion-deletions involving a few base pairs (as is the case for *An. darlingi* from Belize in the present study) or single base point mutations. The identical ITS sequences across all of South America suggest a single panmictic breeding population.

We conclude that samples from Mexico, as well as other Central American populations and those from Colombia, would have to be sequenced to determine whether the small deletion in the Belize population represents isolation by distance, immigration, or extinction events. Isolation by distance could result from Belize populations being near the northern end of a north-south cline or could be due to immigration, or extinction events could be related to the reported discontinuity of *An. darlingi* populations in Central

America. Both distance explanations seem to be relatively weak since there is no evidence of clinal variation (for example, the ITS2 sequence is identical between El Juval in western Venezuela and São Paulo). If the Belize populations had been independently evolving for a long period of time due to an historical vicariant (of different origin) event, variance in the ITS2 from Belize compared with populations in South America should be greater. Therefore, we suggest that the small deletion in the Belize populations of *An. darlingi* is most likely the result of a recent introduction event caused either by human action or some other extrinsic force. Future studies could test this hypothesis by determining which South American populations have the greatest similarity with the Belize populations and whether other Central American and Mexican samples are more similar to populations from Belize or from South America.

The study of head, legs, and wings of 17 populations of *An. darlingi* showed wide variation in morphologic characteristics. On the wing costa, eight different patterns were described based on the presence or absence of one or more spots. Geographic variations in the pattern of the wing costa have been reported for other *Nyssorhynchus* such as *An. albitalis*<sup>67</sup> and *An. nuneztovari*.<sup>68</sup> The Euclidean distances separating groupings of diagnostic wing characters suggest that gene flow occurs among populations across all geographic locations of populations included in these analyses. A previous study<sup>69</sup> on Brazil populations showed that the variations were intraspecific "because no patterns were population specific".

Based on isozyme, RAPD-PCR, ITS2 sequence, and morphologic analyses, all *An. darlingi* populations collected from most parts of the species' range in Central and South America demonstrated a genetic similarity that is consistent with the existence of a single species. While some genetic and morphologic variations were found among the populations surveyed, no complete barriers to gene flow were identified. The relative homogeneity of *An. darlingi* populations might indicate that the isolated population of Central America could have originated from South America. As presently defined, the limited range of *An. darlingi* in Central America suggests a recent introduction of the species. This limited distribution also raises the possibility that the species could, over time, expand into or reinvade more Central American countries and more states in southern Mexico. The former hypothesis could be tested using microsatellites, RAPD-PCR, or ITS2 sequences for the characterization of *An. darlingi* populations throughout southern Mexico, Central and South America to determine more precisely the phylogeny of the species.

**Acknowledgments:** We thank the following individuals for assistance with the field collections: in Belize: S. Hakre and L. Reyes (Epidemiology Research Lab, Belize City); in Bolivia: J. Cespedes, J. Cuba, C. Toffen, and A. Melgar (Unidad Sanitaria, Riberalta); in Brazil: W. A. Alecrim (Instituto de Medicina Tropical, Manaus), W. Tadei (Instituto Nacional de Pesquisas da Amazonia, Manaus), R. Lourenço-de-Oliveira and D. Couto Lima (Fundacao Oswaldo Cruz, Rio de Janeiro), O. P. Forattini and M. A. Mureb Sallum (Universidade de São Paulo), L. C. Meneguetti, F. de Azevedo Corrêa, J. E. Bracco, and E. Berço (Superintendência de Controle de Endemias, São Paulo), A. Cruz Marques, J. Fonseca Sandoval, F. dos Santos, R. Da Luz Lacerda, A. Wanderley, and G. Calderón (Fundacao Nacional da Saude), M. Marins Pova (Instituto Evandro Chagas, Be-

lém); in Colombia: W. Rojas and S. Zuloaga (Cooperación para Investigaciones Biológicas, Medellín), H. Polo (Servicio de Eradicación de Malaria, Chocó); in French Guiana: J.-M. Reynes (Pasteur Institute, Cayenne); and in Venezuela: J. Scorza, E. Rojas, and E. Brown (Universidad de los Andes, Trujillo); J. Mora, J. Espana, J. Aguilar, and C. Menaré (Dirección de Malariología y Saneamiento Ambiental, Maracay), and H. Guzmán and J. Manuel Arcia (Escuela de Malariología y Saneamiento Ambiente, Maracay). We also thank R. E. Harbach who helped in collecting specimens in São Paulo State (Brazil). We are grateful to E. L. Peyton, who provided some voucher specimens of the Smithsonian Institution and for most valuable discussions. Special thanks are due to W. C. Black IV for helping with the RAPD-PCR analysis and to A. Gutierrez for the statistical analysis of the morphologic data.

**Financial support:** This research was sponsored by Uniformed Services University of the Health Sciences (USUHS) grant R087EL to Sylvie Manguin, in part by National Aeronautics and Space Administration (NASA) grant W-16306 for the isozyme study, by NIH grant AI-31034 to L. P. Lounibos (Florida Medical Entomology Laboratory, Vero Beach, FL) and NIH grant AI-40116 to Jan E. Conn for the ITS2 sequencing, by Consejo Nacional de Investigaciones Científicas y Tecnológicas (MPS-RPIV-130032-9), and the Pan American Health Organization for the morphologic study.

**Authors' addresses:** Sylvie Manguin, Laboratoire de Lutte contre les Insectes Nuisibles, ORSTOM, 911 Avenue Agropolis, BP 5045, 34032 Montpellier Cedex 1, France. Richard C. Wilkerson, Walter Reed Biosystematics Unit, Department of Entomology, Walter Reed Army Institute of Research, Washington, DC 20307-5100. Jan E. Conn, Department of Biology, University of Vermont, Burlington, VT 05405-0086. Yasmin Rubio-Palis, Division de Investigaciones, Escuela de Malariología y Saneamiento Ambiental Dr. Arnoldo Gabaldon, Apartado 2073, Maracay 2101-A, Venezuela. James A. Danoff-Burg, Department of Biology, Barnard College, New York, NY 10027. Donald R. Roberts, Department of Preventive Medicine and Biometrics, Uniformed Services University of the Health Sciences, 4301 Jones Bridge Road, Bethesda, MD 20814.

**Reprint requests:** Sylvie Manguin, Laboratoire de Lutte contre les Insectes Nuisibles, ORSTOM, 911 Avenue Agropolis, BP 5045, 34032 Montpellier Cedex 1, France.

#### REFERENCES

1. Foote RH, Cook DR, 1959. Mosquitoes of medical importance. *Agricultural Handbook* 152. Washington, DC: U.S. Department of Agriculture, 1-158.
2. Manguin S, Roberts DR, Andre, RG, Rejmankova E, Hakre S, 1996. Characterization of *Anopheles darlingi* (Diptera: Culicidae) larval habitats in Belize, Central America. *J Med Entomol* 33: 205-211.
3. Linthicum KJ, 1988. A revision of the *Argyritarsis* section of the subgenus *Nyssorhynchus* of *Anopheles* (Diptera: Culicidae). *Mosq Syst* 20: 98-271.
4. Rubio-Palis Y, Zimmerman RH, 1997. Ecoregional classification of malaria vectors in the neotropics. *J Med Entomol* 34: 499-510.
5. de Arruda M, Carvalho MB, Nussenzweig RS, Mararic M, Ferreira AW, Cochrane AH, 1986. Potential vectors of malaria and their different susceptibility to *Plasmodium falciparum* and *Plasmodium vivax* in northern Brazil identified by immunoassay. *Am J Trop Hyg* 35: 873-881.
6. Fleming G, 1986. *Biology and Ecology of Malaria Vectors in the Americas*. PNSP/86-72. Washington, DC: Pan American Health Organization.
7. Forattini OP, 1962. *Entomologia Medica*. Volume 1. São Paulo: Faculdade de Higiene e Saúde Publica.
8. Lourenço-de-Oliveira R, Da Gama Guimarães AE, Arlé M, da Silva TE, Castro MG, Motta MA, Deane LM, 1989. Anopheline species, some of their habits and relation to malaria in endemic areas of Rondonia State, Amazon region of Brazil. *Mem Inst Oswaldo Cruz* 84: 501-514.
9. Alecrim WD, 1992. Malaria, prospecting activities and govern-

- ment policies in the Amazon Region. *Rev Inst Med Trop São Paulo* 34: S48.
10. Root FM, 1926. Studies on Brazilian mosquitoes. I. The anophelines of the *Nyssorhynchus* group. *Am J Hyg* 6: 684-717.
  11. Galvão ALA, Lane J, Correa RR, 1937. Notas sobre os *Nyssorhynchus* de São Paulo. V. Sobre os *Nyssorhynchus* de Novo Oriente. *Rev Biol Hyg* 8: 27-45.
  12. Galvão ALA, Barreto MP, 1939. Contribuição ao conhecimento dos primeiros estádios dos anofelinos de São Paulo. *Rev Biol Hyg* 9: 110-115.
  13. Causey OR, Deane LM, Deane MP, 1944. An illustrated key to the eggs of 30 species of Brazilian anophelines, with several new descriptions. *Am J Hyg* 39: 1-7.
  14. Rubio-Palis Y, Ayesta C, 1996. Ultraestructura del exocorion del huevo de *Anopheles braziliensis* y *Anopheles darlingi* (Diptera: Culicidae) del sur de Venezuela. *Bol Dir Mal San Amb* 36: 64-69.
  15. Forattini OP, 1987. Exophilic behavior of *Anopheles darlingi* Root in a southern region of Brazil. *Rev Saude Publica* 21: 291-304.
  16. Buralli GM, Bergo ES, 1988. Maintenance of *Anopheles darlingi* Root, 1926 colony, in the laboratory. *Rev Inst Med Trop São Paulo* 30: 157-164.
  17. Klein TA, Lima JBP, 1990. Seasonal distribution and biting patterns of *Anopheles* mosquitoes in Costa Marques, Rondonia, Brazil. *J Am Mosq Control Assoc* 6: 700-707.
  18. Rosa-Freitas MG, Broomfield G, Priestman A, Milligan PJ, Momen H, Molyneux DH, 1992. Cuticular hydrocarbons, isoenzymes and behavior of three populations of *Anopheles darlingi* from Brazil. *J Am Mosq Control Assoc* 8: 357-366.
  19. Charlwood JD, 1996. Biological variation in *Anopheles darlingi* Root. *Mem Inst Oswaldo Cruz* 91: 391-398.
  20. Hudson JE, 1984. *Anopheles darlingi* Root (Diptera: Culicidae) in the Suriname rain forest. *Bull Entomol Res* 74: 129-142.
  21. Rozendaal JA, 1990. *Epidemiology and Control of Malaria in Suriname with Special Reference to Anopheles darlingi*. Dordrecht: ICG Printing.
  22. Pajot FX, Le Pont F, Molez JF, Degallier N, 1977. Agressivité d'*Anopheles darlingi* Root, 1926 en Guyane Française. *Cah ORSTOM Ser Entomol Med Parasitol* 15: 15-22.
  23. Rambajan I, 1984. Reappearance of *Anopheles darlingi* Root and vivax malaria in a controlled area of Guyana, South America. *Trop Geogr Med* 36: 61-66.
  24. Quinones ML, Suarez MF, 1990. Indoor resting heights of some anophelines in Colombia. *J Am Mosq Control Assoc* 6: 602-604.
  25. Rubio-Palis Y, 1995. Observaciones sobre el patron de actividad hematofagica del vector de malaria *Anopheles darlingi* en las poblaciones del sur de Venezuela. *Bol Dir Mal San Amb* 35: 66-70.
  26. Faran ME, Linthicum KJ, 1981. A handbook of Amazonian species of *Anopheles* (*Nyssorhynchus*). *Mosq Syst* 13: 1-81.
  27. Harbach RE, Roberts DR, Manguin S, 1993. Variation in the hindtarsal markings of *Anopheles darlingi* (Diptera: Culicidae) in Belize. *Mosq Syst* 25: 192-197.
  28. Kreutzer RD, Kitzmiller JB, Ferreira E, 1972. Inversion polymorphism in the salivary gland chromosomes of *Anopheles darlingi*. *Mosq News* 32: 555-565.
  29. Tadei WP, Santos JMN, Rabbani MG, 1982. Biologia de anofelinos amazônicos. V. Polimorfismo cromossômico de *Anopheles darlingi* Root (Diptera: Culicidae). *Acta Amazon* 12: 353-369.
  30. Steiner WWM, Narang S, Kitzmiller JB, Swofford DL, 1982. Genetic divergence and evolution in neotropical *Anopheles* (Subgenus *Nyssorhynchus*). Steiner WWM, Tabachnick JW, Rai KS, Narang S, eds. *Recent Developments in the Genetics of Insect Disease Vectors*. Champaign, IL: Stipes Publishing Company, 523-550.
  31. Contel EPB, dos Santos JMM, Tadei WP, 1984. Biologia de Anophelinos Amazonicos. VI. Enzimática em *Anopheles darlingi* Root (Dipt.: Culicidae). *Acta Amazon* 14: 238-224.
  32. Dos Santos JM, Tadei WP, Contel EP, 1996. Biology of Amazonian anopheline. XX. Ontogeny of esterases, leucine aminopeptidase and  $\alpha$ -glycerophosphate dehydrogenase in *Anopheles* (*Nyssorhynchus*) *darlingi* Root, 1926 (Diptera, Culicidae). *Rev Bras Biol* 56: 591-598.
  33. Munstermann LE, Conn JE, 1997. Systematics of mosquito disease vectors (Diptera: Culicidae): impact of molecular biology and cladistic analysis. *Annu Rev Entomol* 42: 351-369.
  34. Wilkerson RC, Gaffigan TV, Lima JB, 1995. Identification of species related to *Anopheles* (*Nyssorhynchus*) *albiparvus* by random amplified polymorphic DNA-polymerase chain reaction (Diptera: Culicidae). *Mem Inst Oswaldo Cruz* 90: 721-732.
  35. Wilkerson RC, Parsons TJ, Klein TA, Gaffigan TV, Bergo E, Consolim J, 1995. Diagnosis by random amplified polymorphic DNA polymerase chain reaction of four cryptic species related to *Anopheles* (*Nyssorhynchus*) *albiparvus* (Diptera: Culicidae) from Paraguay, Argentina and Brazil. *J Med Entomol* 32: 697-704.
  36. Gawel NJ, Bartlett AC, 1993. Characterization of differences between whiteflies using RAPD-PCR. *Insect Mol Biol* 2: 33-38.
  37. Lu R, Rank GH, 1996. Use of RAPD analyses to estimate population genetic parameters in the alfalfa leaf-cutting bee, *Megachile rotundata*. *Genome* 39: 655-663.
  38. Baruffi L, Damiani G, Guglielmino CR, Bandi C, Malacrida AR, Gasperi G, 1995. Polymorphism within and between populations of *Ceratitis capitata*: comparison between RAPD and multilocus enzyme electrophoresis data. *Heredity* 74: 425-437.
  39. Fritz GN, Conn J, Cockburn AF, Seawright JA, 1994. Sequence analysis of the rDNA internal transcribed spacer 2 from geographic strains of *Anopheles nuneztovari* (Diptera: Culicidae). *Mol Biol Evol* 11: 406-416.
  40. Paskewitz SM, Wesson DM, Collins FH, 1993. The internal transcribed spacers of ribosomal DNA in five members of the *Anopheles gambiae* species complex. *Insect Mol Biol* 2: 247-257.
  41. Cornel AJ, Porter CH, Collins FH, 1996. Polymerase chain reaction species diagnostic assay for *Anopheles quadrimaculatus* cryptic species (Diptera: Culicidae) based on ribosomal DNA ITS2 sequences. *J Med Entomol* 33: 109-116.
  42. Manguin S, Roberts DR, Peyton EL, Fernandez-Salas I, Barreto M, Fernandez Loayza R, Elgueta Spinola R, Martinez Granaou R, Rodriguez MH, 1995. Biochemical systematics and population genetics of *Anopheles pseudopunctipennis*, vector of malaria in Central and South America. *Am J Trop Med Hyg* 53: 362-377.
  43. Clayton JW, Tretiak DN, 1972. Amine-citrate buffers for pH control in starch gel electrophoresis. *J Fish Res Board Can* 29: 1169-1172.
  44. Siciliano MJ, Shaw CR, 1976. Separation and visualization of enzymes on gels. Smith I, ed. *Chromatographic and Electrophoretic Techniques*. Volume 2. New York: William Heinemann Med. Books Ltd., 185-209.
  45. Swofford DL, Selander RB, 1989. BIOSYS-1. A Computer Program for the Analysis of Allelic Variation in Population Genetics and Biochemical Systematics. Champaign, IL: Illinois Natural History Survey.
  46. Nei M, 1978. Estimation of average heterozygosity and genetic distance from a small number of individuals. *Genetics* 89: 583-590.
  47. Rogers JS, 1972. Measures of genetic similarity and genetic distance. *Studies in Genetics. Univ Texas Publ* 7213: 145-153.
  48. Wilkerson RC, Parsons TJ, Albright DG, Klein TA, Braun MJ, 1993. Random amplified polymorphic DNA (RAPD) markers readily distinguish cryptic mosquito species (Diptera: Culicidae: *Anopheles*). *Insect Mol Biol* 1: 205-211.
  49. Black IV WC, 1996. Statistical analysis of arbitrarily primed PCR patterns in molecular taxonomic studies. Clapp JR, ed. *Species Diagnostics Protocols. Methods in Molecular Biology*. Volume 50. Totowa, NJ: Humana Press, 39-55.
  50. Nei M, Li WH, 1985. Mathematical model for studying genetic variation in terms of restriction endonucleases. *Proc Natl Acad Sci USA* 76: 5269-5273.
  51. West DF, Black IV WC, 1998. Breeding structure of three snow-

- pool melt *Aedes* mosquito species in northern Colorado. *Hereditas* 81: 371-380.
52. Collins FH, Mendez MA, Rasmussen MO, Mehaffey PC, Besansky NJ, Finnerty V, 1987. A ribosomal RNA probe differentiates members of the *Anopheles gambiae* complex. *Am J Trop Med Hyg* 37: 37-41.
  53. Porter CH, Collins FH, 1991. Species-diagnostic differences in a ribosomal DNA internal transcribed spacer from the sibling species *Anopheles freeborni* and *Anopheles hermsi* (Diptera: Culicidae). *Am J Trop Med Hyg* 45: 271-279.
  54. Harbach RE, Knight KL, 1980. *Taxonomists' Glossary of Mosquito Anatomy*. Marlton, NJ: Plexus Publishing, Inc.
  55. Harbach RE, Knight KL, 1982. Corrections and additions to taxonomists' glossary of mosquito anatomy. *Mosq Syst* 13: 201-217.
  56. Wilkerson RC, Peyton EL, 1990. Standardized nomenclature for the costal wing spots of the genus *Anopheles* and other spotted-wing mosquitoes (Diptera: Culicidae). *J Med Entomol* 27: 207-224.
  57. Program Statistica, 1993. *Program for Windows 4.5*. Statsoft, Inc., Uppsala, Sweden: Uppsala University.
  58. Legendre L, Legendre P, 1983. *Numerical Ecology*. New York: Elsevier Publishers.
  59. Peyton EL, Wilkerson RC, Harbach RE, 1992. Comparative analysis of the subgenera *Kerteszia* and *Nyssorhynchus* of *Anopheles* (Diptera: Culicidae). *Mosq Syst* 24: 51-69.
  60. Graur D, 1985. Gene diversity in Hymenoptera. *Evolution* 39: 190-199.
  61. Avise JC, 1975. Systematic value of electrophoretic data. *Syst Zool* 23: 465-481.
  62. Cianchi R, Villani F, Toure YT, Petrarca V, Bullini L, 1983. Electrophoresis study of different chromosomal forms within *Anopheles gambiae* s.s. *Parasitologia* 27: 157-167.
  63. Bullini L, 1984. Enzyme variants in the identification of parasites and vectors: methodological aspects of the electrophoretic approach. Newton BM, Michael FF, eds. *Tropical Disease Research*. Geneva: World Health Organization, 53-69.
  64. Smits A, Roelants P, Van Bortel W, Coosemans M, 1996. Enzyme polymorphisms in the *Anopheles gambiae* (Diptera: Culicidae) complex related to feeding and resting behavior in the Imbo Valley, Burundi. *J Med Entomol* 33: 545-553.
  65. Wright S, 1978. *Evolution and the Genetics of Populations*. Volume 4. *Variability Within and Among Natural Populations*. Chicago: University of Chicago Press.
  66. Conn JE, Mitchell SE, Cockburn AF, 1998. Mitochondrial DNA analysis of the neotropical malaria vector *Anopheles nuneztovari*. *Genome* 41: 313-327.
  67. Rosa-Freitas MG, Deane LM, Momen H, 1990. A morphological, isoenzymatic and behavioral study of ten populations of *Anopheles* (*Nyssorhynchus*) *albiparvus* Lynch-Arribalzaga, 1878 (Diptera: Culicidae) including from type-locality Baradero, Argentina. *Mem Inst Oswaldo Cruz* 85: 275-289.
  68. Hribar L, 1995. Costal wing spot variation within and among progeny of single female *Anopheles nuneztovari* (Diptera: Culicidae). *Mosq Syst* 27: 1-15.
  69. Rosa-Freitas-Sibajev MG, Conn J, Mitchell SE, Cockburn AF, Seawright JA, Momen H, 1995. Mitochondrial DNA and morphological analyses of *Anopheles darlingi* populations from Brazil (Diptera: Culicidae). *Mosq Syst* 27: 78-99.
  70. Faran ME, 1980. Mosquitoes studies (Diptera: Culicidae) 34: a revision of the *Albimanus* section of the subgenus *Nyssorhynchus* of *Anopheles*. *Contrib Am Entomol Inst* 15: 1-215.



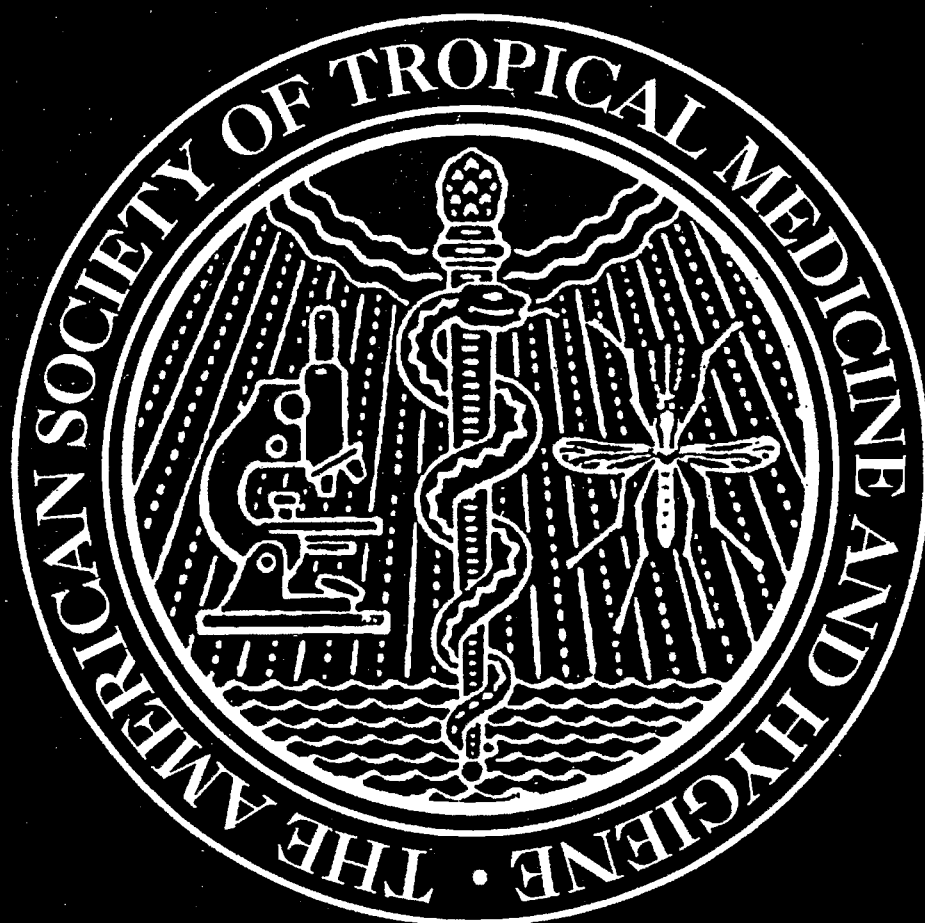
ISSN= 0008-9637

VOLUME 60

MARCH 1999

NUMBER 3

*The American Journal of*  
**TROPICAL  
MEDICINE &  
HYGIENE**



PM 86  
13 AVR. 1999

Sante

OFFICIAL JOURNAL OF  
THE AMERICAN SOCIETY OF TROPICAL MEDICINE AND HYGIENE

