Original Article

Sporogonic Cycles Calculated Using Degree-Days, as a Basis for Comparison of Malaria Parasite Development in Different Eco-Epidemiological Settings in India

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SUMMARY: In India, malaria transmission is prevalent across diverse geologies and ecologies. Temperature is one of the key determinants of malarial transmission, causing low endemicity in some areas than in others. Using a degree-day model, we estimated the maximum and minimum possible number of days needed to complete a malarial sporogonic cycle (SC), in addition to the possible number of SCs for *Plasmodium vivax* and *Plasmodium falciparum* under two different ecological settings with either low or high endemicity for malaria at different elevations. In Raikhalkhatta (in the Himalayan foothills) SCs were modeled as not occurring from November to February, whereas in Gandhonia village (forested hills), all but only one month were suitable for malarial SCs. A minimum of 6 days and maximum of 46 days were required for completion of one SC. Forested hilly areas were more suitable for malaria parasite development in terms of SCs (25 versus 21 for *P. falciparum* and 32 versus 27 for *P. vivax*). Degree-days also provided a climatic explanation for the current transmission of malaria at different elevations. The calculation of degree-days and possible SC has applications in the regional analysis of transmission dynamics and management of malaria in view of climate change.

INTRODUCTION

India has 6 major endemic vector borne diseases: malaria, dengue, lymphatic filariasis, visceral leishmaniasis, Japanese encephalitis, and chikungunya fever. Of these, malaria shows both the highest morbidity and geographical range. The distribution of malaria reveals very high endemicity in eastern India, whilst endemicity is very low in western and northern parts of the country (1). This heterogeneity in the distribution of malaria is linked to climatic factors, which affect the distribution and abundance of mosquito vectors and subsequent development of the malaria parasite (2). Of various climatic parameters, temperature, relative humidity, and rainfall have been highlighted as important determinants of malaria transmission (3–6). Across temperature ranges, the developmental rate of malaria parasites and vector species also varies (7–10). Most existing studies investigating the impact of climatic variables on vector or malaria transmission, have considered the average monthly temperature (11–13). Recent studies, however, have shown that mosquito and parasite biology are influenced by daily variations in temperature (14) rather than the average monthly temperature. The impact of daily temperature on the sporogony of malaria parasites has been previously studied almost seven decades ago (15). In this study, variation was expressed as degree-days, the sum of heat required for completion of sporogonic cycle (SC) in malaria vectors. Climate

change is expected to impact disease spread; therefore, it is imperative to assess the influence of temperature on malaria transmission. In this study, we examined how environmental temperature influences the extrinsic incubation period for malaria parasites in terms of degree-days required for completion of SC in two different eco-epidemiological settings in India.

MATERIALS AND METHODS

This study was performed in one village each of the states of Uttarakhand and Jharkhand, located in the Himalayan foothills. The village in Uttarakhand showed high temperature variations and low malarial endemicity, whereas the village in Jharkhand included warmer forested area with high endemicity for the disease. The village Raikhalkhatta, Uttarakhand (located at N 29° 04'9.41" & E 79°39'1.02"; elevation: 339 m), was randomly chosen in the jurisdiction of Primary Health Center (PHC) Motahald in the foothills of the Nainital district. The village Gandhonia, Jharkhand (located at N 23°30'19.2" & E 85°35'48.5"; elevation: 648 m) was randomly selected in the Ramgarh PHC area in the forested hills of the Ramgarh district (Fig 1). To record hourly indoor temperature in the villages, HOBO data-loggers (MicroDaq, Contoocook, NH, USA) were fixed inside the corner of human dwellings at a height of 2 m, where mosquitoes were usually found to rest. The temperature was recorded from January 2013 to February 2014 in Raikhalkhatta and from June 2013 to June 2014 in Gandhonia. Mean daily temperature was calculated from the hourly data recorded.

Based on the generated daily temperature, the degree-days required for completion of sporogony of *Plasmodium vivax* and *Plasmodium falciparum* were calculated using Indirect Moshkovsky's Method (16). The direct method for estimation of duration of sporogony uses experimental conditions at constant temperature,

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whereas the indirect method estimates the duration of sporogony in the natural habitats of epidemiological significance. The duration of sporogony is represented by the number of days necessary to obtain the sum of heat required for development by a given species (Indirect Moshkovsky's Method). The number of degree-days was calculated by subtracting the estimated lowest development threshold temperature recorded in 24 h from the daily mean temperature recorded indoors in both the study sites. The estimated lowest development threshold was considered to be 14.5°C for *P. vivax* and 16°C for *P. falciparum*. If the mean temperature is 25°C, the degree-day for *P. vivax* will be $25 - 14.5 = 10.5^\circ\text{C}$. The sum of heat in degree-days necessary for the SC has been reported to be 105°C for *P. vivax*, 111°C for *P. falciparum*, and 144°C for *Plasmodium malariae* (16).

Fig. 1. Malaria endemicity in India based on Annual Parasite Incidence (API; 2010–2012) (data source: National Vector Borne Disease Control Program [NVBDCP]). Study areas have been marked on the map i.e., Nainital district (API = 0.01–2.00 per 1,000 population) and Ramgarh district (API = 10.01–20.00).

RESULTS

Based on the temperature recorded ($^\circ\text{C}$) in a natural mosquito resting place, the number of possible sporogonic cycles (SCs) in a year was calculated using Moshkovsky's method (Table 1). In Raikhalkhatta village in Himalayan foothills (Nainital district) 27 SCs of *P. vivax* and 21 SCs for *P. falciparum* were possible under the conditions observed. On the other hand, in Gandhonia village in forested hills (Ramgarh district), 32 and 25 SCs were possible for *P. vivax* and *P. falciparum*, respectively. The maximum number of possible SCs was lower for *P. falciparum* than *P. vivax* in both villages studied (Table 1). The relationship between seasonality of malaria cases and the number of SCs in a year in both the localities was also analyzed. This revealed an extended and year-round transmission of malaria in the forested hills in Gandhonia, compared to 7 months of transmission in Raikhalkhatta located in Himalayan foothills (Fig. 2 and 3).

One SC was completed in 9.0 ± 3.1 days for *P. vivax* and 11.1 ± 4.7 days for *P. falciparum* at Raikhalkhatta. In comparison, in Gandhonia, 10.4 ± 6.7 days and 9.8 ± 7.1 days were required for single *P. vivax* and *P. falciparum* SCs, respectively. Using the calculation of degree-days, a minimum of 6 days and a maximum of 46 days was required for completion of one SC in the study villages (Table 1). The temporal trend of malaria data collected from the respective PHCs of both study villages also reflected difference in the seasonal trend and intensity of malaria cases in the two villages (Fig. 2 and 3). A higher incidence of malaria cases was recorded throughout the study period in Ramgarh PHC where Gandhonia is located than in Motahaldu PHC where Raikhalkhatta is located.

DISCUSSION

Few studies have investigated the temperature dependence of extrinsic incubation periods of *P. falciparum* and *P. vivax* in various mosquito species harboring either of these parasites (14). Gething et al. used a degree-day model to estimate the transmission of *P. falciparum* and *P. vivax* at a global level (3). LaPointe et al. used the degree-day model in determining sporogonic development of *Plasmodium relictum* in avian malaria parasites (17). In addition, Moore et al., while working on the population model of intermediate host of *Schistosoma japonicum*, cautioned that the results of

Table 1. Possible number of sporogonic cycles in a year using temperature of natural resting places in Raikhalkhatta and Gandhonia villages in India

Malaria parasite	Date of data generation	Location (village/PHC)	Period required for completion of sporogony (days)			Possible sporogonic cycles in a year ³⁾
			Mean	Max	Min	
<i>P. vivax</i>	Jan. 2013–	Raikhalkhatta ¹⁾	9.0 ± 3.1	23	6	27
<i>P. falciparum</i>	Feb. 2014	/Motahaldu	11.1 ± 4.7	31	7	21
<i>P. vivax</i>	Jun. 2013–	Gandhonia ²⁾	10.4 ± 6.7	38	6	32
<i>P. falciparum</i>	Jun. 2014	/Ramgarh	9.8 ± 7.1	46	8	25

¹⁾ Low endemic area in Himalayan foothill. ²⁾ Forested hill area with high malaria endemicity.

³⁾ The method for calculation of sporogonic cycles is mentioned in the method section.

Fig. 2. Possible number of sporogonic cycles (SCs) for *P. falciparum* (*Pf*) and *P. vivax* (*Pv*) in Raikhalkhatta (Nainital district), Uttarakhand state. Being low endemic area negligible number of *P. vivax* cases was reported. Malaria cases reported by the primary health center (PHC) indicate a lag period of roughly one month with SC.

Fig. 3. Possible number of sporogonic cycles (SCs) for *P. falciparum* (*Pf*) and *P. vivax* (*Pv*) in Gandhonia (Ramgarh district), Jharkhand state. Lag period between cases and SC appears to be 2 months.

prediction of disease based on the degree-day model in view of climate change should be considered most reliable when the temperature ranges used in a projection resemble those used to estimate model parameters (18). It is important to point out here that the micro-niche of mosquitoes is strictly not outdoors, while climate change projections are based on sensors installed outdoors (19). Therefore, the climate change projections may not be exactly applied for indoor resting malaria vectors. In the present study, the daily indoor temperature from two localities has been used to demonstrate the difference in possible length and number of SCs, thereby highlighting the significance of using local temperature data for determining the transmission of malaria. This is very well corroborated by the difference in the number of SCs in two different ecological settings.

The findings of this study reveal that the temperature at Gandhonia (Jharkhand) was more favorable for the parasite development than that at Raikhalkhatta (Uttarakhand), thus resulting in a greater number of possible SCs, and the extended transmission of malaria as observed in Ramgarh PHC having Gandhonia village

(Fig. 3). The minimum and maximum number of days required for the completion of one SC was calculated as 6 and 46 days. In nature, neither the mosquito vector can normally survive for 46 days nor could the SC, be completed in 6 days (7). This finding indicates that there are some unsuitable days in a year when transmission may not be possible (Fig. 3) because of extreme high and extreme low temperatures. SCs could not be established in Gandhonia village in January 2014, whereas only one SC could be established in December 2013 and February 2014 (Fig. 3). This is reflected by the small number of malaria cases (*P. falciparum*) in subsequent months from January to May. In Raikhalkhatta, November to February months were not suitable even for a single SC, which is reflected by the near absence of malaria cases. The malaria cases reported in November may be attributed to the effect of lag period in the previous month, where 2 or 3 SCs could have been established.

The reason for high endemicity in states like Jharkhand (as represented by the district Ramgarh in the present study) is explained by the possibility of more SCs occurring due to the relatively more conducive temperature than that at the foothills of Uttarakhand which

have lower temperatures during the winter spell. In view of projected rises in temperatures (20), it becomes imperative to calculate the degree-days and number of SCs for different eco-epidemiological areas. This will facilitate appropriate planning of vector control operations, such as the numbers of rounds of indoor residual spraying if required. Owing to differences in the number of possible SCs at the two different locations used in the present study, more studies are required to optimize appropriate time of indoor residual spraying.

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Conflict of interest None to declare.

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