EL NIÑO AND ASSOCIATED OUTBREAKS OF SEVERE MALARIA IN HIGHLAND POPULATIONS IN IRIAN JAYA, INDONESIA: A REVIEW AND EPIDEMIOLOGICAL PERSPECTIVE

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Abstract. Perennial malaria is a major public health problem for most coastal, lowland and foothill populations in Irian Jaya (western New Guinea), the largest and easternmost province of Indonesia. Malaria at higher elevations above 1,500 m is considered intermittent and highly unstable, providing a constant threat of epidemics. Beginning in late August 1997, a significant increase of unexplained deaths was reported from the central highland district of Jayawijaya. The alarming number of fatalities rapidly escalated into September, dropping off precipitously by late October. More than 550 deaths due to "drought-related" disease had been officially reported from the district during this 10-week period. The outbreaks occurred in extremely remote areas of steep mountainous terrain inhabited by primitive shifting agriculturist populations. Microscopical evidence and site survey data implicated malaria as the principal cause of the excess morbidity and mortality at elevations between approximately 1,000 and 2,200 m.

The dramatic increase in malaria and associated deaths was indirectly related to the prolonged and severe drought created by the prevailing 1997-98 El Niño Southern Oscillation (ENSO) affecting the Australasian region. Clinical cases of malaria were described as severe, due, in large part to the low level of naturally acquired immunity (NAI) in these highland populations and the predominance of *Plasmodium falciparum* infection. Disease may have been further exacerbated by the population's compromised nutritional status because of severe shortages of staple foods affected by the drought. Based on a retrospective investigation, an 'a posteriori' epidemiological explanation of the probable, interrelated causes of the epidemic is presented. Beginning in late July 1997, drought conditions resulted in numerous, transient pools of standing water along zones of steep gradient streams normally associated with fast-flowing water. This permitted sufficient and rapid increases in vector populations (*Anopheles punctulatus* complex) that either could sustain recently introduced or intensified local low-level malaria transmission. Moreover, water and food shortages contributed to increased demographic movement and exposure to high risk malaria endemic lowlands, thus increasing the prevalence of human infections and infectious reservoirs in those populations returning to the highlands. The eventual rapid drying and elimination of the vector larval habitats along stream beds, combined with mass antimalarial drug distribution are believed, in part, to be responsible for the rapid decline of severe malaria and related deaths.

Area delimited and isolated focal outbreaks of malaria are recognized as occasional, periodic events in these highlands. This epidemic produced great concern because of the broad regionalized extent of the problem, the culmination of many independent outbreaks occurring during the same period that overwhelmed the local health care and control capabilities. We predict communicable disease outbreaks, including malaria, may likely increase in periodicity in the Irian Jaya highlands as socioeconomic development and population movements increase. This investigation further underscores the importance of malaria and its impact on presumed NAI deficient highland populations. Furthermore, the association of ENSO-related climatic anomalies and heightened infectious disease transmission is illustrative of how rapidly changing local weather events can dramatically alter disease patterns. These circumstantial findings, albeit important, point to the urgent need for more definitive understanding of highland malaria dynamics, the development of a sustainable longitudinal surveillance system, and appropriate outbreak response capabilities for the highlands of Irian Jaya.

INTRODUCTION

Malaria remains one of the most important infectious diseases throughout the tropical and sub-tropical world. Worldwide, between 300-500 million clinical cases and an estimated more than 2 million people dies each year from the disease (Campbell, 1997). Perennial, hyper to holoendemic malaria is a major public health problem for most coastal, lowland and foothill populations (< 1,000 m) in Irian Jaya (western New Guinea), the largest

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and easternmost province of Indonesia (Gunawan, 1985). Malaria transmission in areas between 1,000-1,500 m (3,280-4,925 ft) above sea level (asl) are generally considered unstable, with moderate to low levels of seasonal malaria transmission. Locations above 1,500 m are often either free of autochonthous malaria or nearly so despite the presence of potential vectors up to 2,250 m (Bonne-Webster, 1948). At these higher elevations, the average lower ambient temperatures generally are considered inadequate for completion of the latent period (parasite extrinsic development) within the average life span of the vector (Metselaar, 1959; Molineaux, 1988). In neighboring Papua New Guinea (PNG) the upper limit of potential malaria transmission is considered to be between 1,800 and 2,000 m (5,900-6,560 ft) (Peters *et al*, 1958). The altitudinal extremes of transmission in Irian Jaya are not well defined and malaria transmission in the central highlands has seldom been investigated (Metselaar, 1959; Maffi *et al*, 1975; Anthony *et al*, 1992).

The highlands of New Guinea are located along the east-west central cordillera that runs the principal length of the island. Except for the larger valleys, most highland villages are located on steep, well-drained locations, which normally provide few suitable *Anopheles* larval habitats. However, most subsistence vegetable gardens typically occupy lower elevations, away from the villages, near higher water tables and streams. Malaria, when present, appears to be greater on valley floors than on hill slopes (Gunawan, 1985; Metselaar, 1959). Local variations in highland transmission risk below 1,500 m are believed to be common due to the varying nature of the terrain, seasonality and degree of socioeconomic development (Anthony *et al*, 1992; Radford *et al*, 1976). These zones of highly unstable transmission are sensitive to climatic variations that can periodically contribute to intermittent episodes of severe and epidemic malaria in New Guinea (Peters *et al*, 1958; Van Dijk and Parkinson, 1974). Unusual climatic conditions can tip the balance in favor of malaria transmission allowing a rapid, although generally brief, epidemic spread of disease into higher elevations (Garnham, 1948). Incursions of malaria into normally unstable or nonendemic areas can produce dramatic focal and widespread outbreaks, generally intensifying disease severity with increasing elevation.

Beginning in late August 1997, the Irian Jaya provincial health department reported a dramatic increase of unexplained deaths from the central highland district of Jayawijaya (Fig 1). The high

Fig 1–Map of Irian Jaya Province, Indonesia and the central highland district of Jayawijaya. Arrow indicates general locality of August-October 1997 outbreak.

death rates were seen commensurate with severe drought conditions and food shortages associated with the 1997 period of an El Niño Southern Oscillation (ENSO). Reported clinical symptoms ranged from severe diarrhea as suspected "cholera", acute respiratory infections as suspected "influenza or pneumonia", to suspected bacterial/viral meningitis. The alarming number of fatalities rapidly escalated through September, before dropping off precipitously by late October. The abbreviated episodes occurred in extremely remote areas of steep mountainous terrain inhabited by small, isolated aboriginal communities. The size and scope of these deadly outbreaks were considered very unusual, quickly alerting the local missionaries and health authorities to the severity of the problem. We investigated the apparent causes of these spatially scattered and isolated outbreaks of severe disease among native populations. Based on concurrent and retrospective epidemiological information, an a posteriori explanation of the precipitating causes of this unusual event is presented herein.

MATERIALS AND METHODS

This investigation took placed shortly after the height of the outbreak in the highland district of Jayawijaya, Irian Jaya Province, Republic of Indonesia. The outbreak was measured principally by reported severe disease and deaths. Mortality data served as the primary indicator of severe disease occurrence as most clinical diagnoses were subjective and not confirmed by any reliable method. As a rule, general morbidity data is not routinely complied. Death is reported within 5 symptomatic categories- diarrhea, acute respiratory illness (ARI), malaria, pneumonia, and unknown or "other" causes (*eg* accidental, natural). Under normal circumstances, diagnostic confirmation is rarely performed and is restricted to the one district hospital in Wamena and a few isolated mission clinics. Likewise, post-mortem or verbal autopsy examinations are not routinely performed at health center facilities.

Compiled unpublished records of concurrent and retrospective information from various field and local missionary reports was provided by the health department in Wamena, the district's administrative center. On-site observations were based on patient clinical presentations and microscopical blood examinations in both random and more detailed site-specific surveillance activities during and after the height of reported deaths. Blood slides from affected areas were collected during the height of the outbreak period. Slides were stained and examined and samples later cross-checked by independent, expert microscopy for accuracy. Daily weather and climate summaries from 1973 to the end of 1997 were obtained from the Wamena meteorological station in the Baliem Valley located at 1,600 m asl. Whenever possible, mosquito vector collections were attempted in some of the more accessible villages. *Anopheles* mosquitos were identified to species and examined individually (head-thorax portion) for *P. falciparum* and *P. vivax* circumsporozoite proteins (*ie* sporozoites) using an ELISA technique (Wirtz *et al*, 1987). Species identification was based on standard morphological criteria (Belkin, 1962) and use of a polymerase chain reaction-restriction fragment length polymorphism (PCR-RFLP) analysis to differentiate sibling species of the *Anopheles punctulatus* complex (Beebe and Saul, 1995). All available data considered reliable was analyzed using descriptive statistics.

RESULTS

Disease and mortality data

The regionalized outbreak appeared concentrated in the highland district of Jayawijaya, southeast of Wamena, in the mountainous subdistricts of Ninia and Kurima (Fig 1). Assembled health teams investigated those villages reporting the greatest excess disease and mortalities at elevations between approximately 1,000 and 2,200 m. Between late August and November 1997 (weeks 35-48), approximately 554 "drought-related" deaths were officially reported from the district (Fig 2). Before August, previous months had reported an average of less than 4 deaths per week. A sharp rise in the outbreak curve was seen on week 38 (September 14-20), culminating in 254 fatalities. This was followed by a significant drop the following week to 56 deaths and rising again for a second peak during week 40 (28 September-04 October) to 160 fatalities. A precipitous drop in reported deaths below 17 per week followed the second peak. Week 49 (December 01-07) had no reports of death. Under normal periods, weekly reported deaths number less than 5-10 per week.

For the purposes of rate estimation, the entire denominator population (estimated ~95,000) covering the general outbreak areas was considered 'at risk' for severe disease. A conservative crude mortality rate of nearly six per 1,000 occurred over a 10-week period. Sex and approximate age were reported for only 211 of the deaths and were used to generate crude sex and age-specific profiles. Denominator data (sex and age-specific population at risk) was not known, so precluding rate calculations. Deaths were seen among all ages (Fig 3); however, the youngest (1-4) and oldest (>35) age

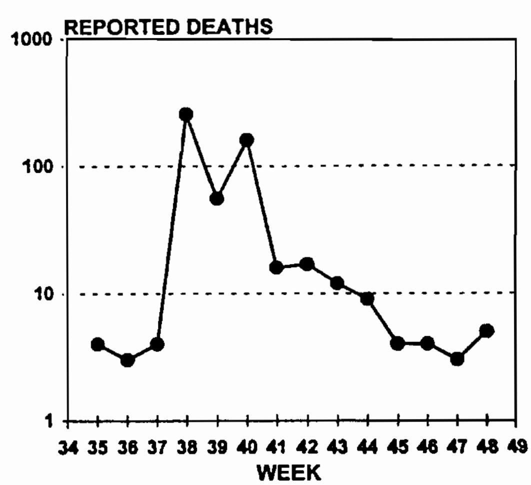

Fig 2–All reported drought-related deaths ($\log_{10}$ scale) during the height of the highland epidemic beginning week 35 (24-30 August) to week 49 (1-7 December) 1997 as reported from 25-32 health stations in Jayawijaya district, Irian Jaya.

groups appeared to suffer a disproportionately higher mortality with reported diarrhea/ARI and ARI, respectively. Males showed a higher number of deaths compared to females (122 *vs* 89) from all presumptive causes of death, with the exception of clinical "malaria" (Fig 4).

Epidemiological surveys

Increased malaria coincided with a period of a dramatic deficit in precipitation associated with the ENSO. Disease symptoms as described in this epidemic were typical of the protean manifestations exhibited by severe disease caused by malaria (Benenson, 1995). Investigations of reports of cholera and bacterial/viral meningitis proved negative

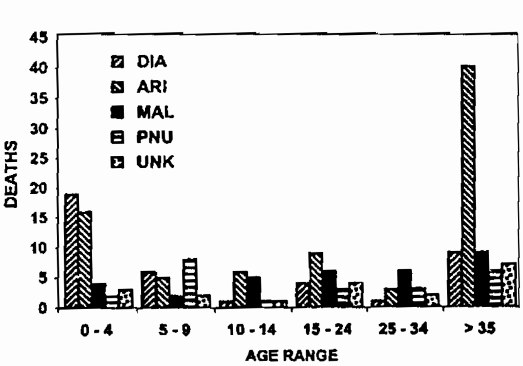

Fig 3–Deaths reported by age-group and presumptive clinical cause during August-October 1997 in Jayawijaya district, Irian Jaya, Indonesia. Diarrhea (DIA), acute respiratory infection (ARI), malaria (MAL), pneumonia (PNU), unknown/other (UNK).

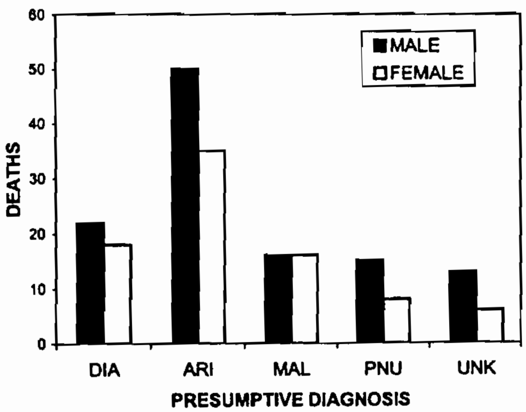

Fig 4–Deaths reported by sex and presumptive clinical cause during August-October 1997 in Jayawijaya district, Irian Jaya, Indonesia. Diarrhea (DIA), acute respiratory infection (ARI), malaria (MAL), pneumonia (PNU), unknown/other (UNK).

(NAMRU-2 and district health office, unpublished data, 1997). Investigations into possible viral upper respiratory disease were limited under the prevailing logistical constraints.

Over the course of several months during and shortly following the outbreak (excess mortality) period, thousands of blood slides were taken as either passive and active case detection (PCD and ACD) for malaria. Some slides results were excluded from analysis because of large discrepancies in slide staining quality, poor condition, and initial examination results by poorly qualified microscopists. The total number of slides collected was difficult to ascertain because of inconsistent reporting of slide numbers and results, and the large number of independent groups (government and non-government agencies) involved in the assessment effort. However, based on 1,890 reviewed blood slide results, *Plasmodium falciparum* infections represented > 75% of all positive cases in both PCD and ACD surveillance, and over 80% of examined clinical (symptomatic) malaria cases were diagnosed *P. falciparum*. Mixed (multiple) species infections were uncommon. Less than 1% of patients presented with patent *P. malariae* or *P. ovale* infections. Based on a random sampling of cross-checked blood slides (n= 608) collected during the height of the outbreak, the gametocyte (reservoir) rates for *P. falciparum* were found high, ranging from 25 to 49%. Examination for enlarged spleens were done only sporadically in some of the affected villages. Detectable enlargement was evident in many of the villagers. Average enlarge spleen (AES) were generally between Hackett's scores 1-2 in all reported areas. Individual statistics from post-outbreak transect highland community surveys will be presented at a later date.

Weather patterns

Weather parameters were greatly influenced by the 1997 period of El Niño. From August to November 1997, a 75% and 70% overall reduction in the normal (1973-96) rainfall and rain days, respectively, was seen (Fig 5). The combination of rainfall and rain days calculated as a 'wetness index' (Russell *et al*, 1963) shows a similar depression in amount and distribution of rainfall during the drought months compared with means from previous years (Fig 6). Maximum and minimum temperatures also showed dramatic deviations in both extremes from averaged previous years (Fig 7). Above normal monthly maximum daytime temperatures were recorded during August through November, with increases of 0.55, 1.1, 2.1, and 1.0°C, respectively. However, the minimum ambient air temperatures

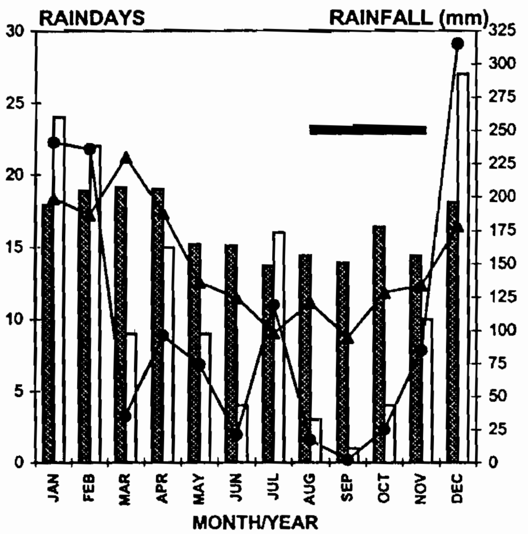

Fig 5–1973-1996 average rainfall in millimeters (▲) and average rain days (lined bar) by month compared to absolute 1997 rainfall (●) and rain days (solid bar) in Wamena, Irian Jaya. Bar (■) corresponds to approximate 14-week time period depicted in Fig 2.

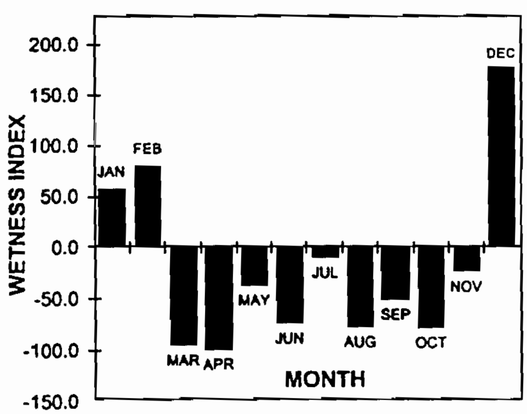

Fig 6–Annual precipitation deviation in Wamena, Irian Jaya, measured as a degree of 'wetness index' with respect to monthly 1973-96 mean (baseline = 0.0) compared to matched monthly indices in 1997. Monthly index computed as total rainfall x total rain days / total days in month. Those months below the baseline represent decreased rainfall and rain days.

were far below normal by minus 2.7, 2.0, 1.5 and 0.1°C for this same period. A net loss/gain of temperature from August to November was -2.15, -0.9, +0.6 and +0.9°C. The fluctuation between max-min temperatures was greatest during September and October (15.1 and 15.4°C) compared to previous years (12 and 11.8°C). Daily air temperatures were

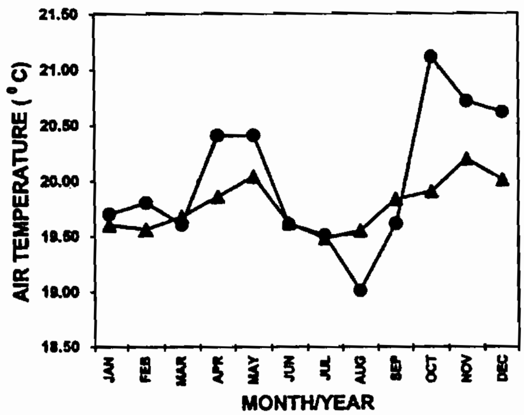

Fig 7–Average 24-hours air temperature by month for 1973-96 (▲), compared to 1997 (●) in Wamena, Irian Jaya, Indonesia.

averaged over 4 time periods each 24-hours period to produce monthly means. Averaged air temperatures fluctuated above and below the previous 24-year trend values for most of 1997 (Fig 7). During the period of lowest rainfall, August and September saw below normal (-0.54 and -0.32°C) temperatures, whereas October and November recorded temperatures far above normal (+1.21 and +0.52°C). The lowest average monthly temperature (19°C) occurred in August. From April to December, barometric pressures were noticeably elevated 0.5 to 2.5 millibars from average monthly values (834-835 mb), with maximum levels seen between August and November.

Entomological findings

Collections for potential mosquito vectors were hampered by logistics, limited trained manpower and generally low human-landing densities. Captures of less than 10-20 adult anophelines per all-evening collections (< 1.0/human/hour) were common. However, *Anopheles* larvae were identified from temporary pools that had formed in stream beds in several malaria affected communities. All adults and larvae that were subjected to PCR-RFLP and were identified as either *Anopheles punctulatus* (s.s.) or *Anopheles farauti* No.6. Despite the common occurrence of *An. farauti* No. 6 in the Wamena (Baliem Valley) area (Bangs, unpublished data, 1997), this sibling species was generally less common in those areas experiencing high malaria rates. Larvae collected from shallow temporary pools of exposed sunlit water, were all identified as *An. punctulatus*. Circumsporozoite protein for *P. falciparum* (*ie*, sporozoites) was detected by ELISA from one *An. punctulatus* captured at approximately 1,700 m in the outbreak area (Bambang Ristyanto, unpublished data, 1997).

DISCUSSION

The 1997-98 ENSO, that resulted in a protracted drought in New Guinea, is regarded as the most severe this century (Webster and Palmer, 1997). Our findings showed a strong temporal association with the ENSO-related climatic anomalies contributing indirectly to heighten malaria exposure and severe disease in highly susceptible highland populations. Sufficient increases in vector populations would likely have been responsible for briefly sustaining recently introduced malaria or intensifying low level, hypoendemic transmission in highland localities normally unaccustomed to malaria. Drought lead to a severe disruption of staple food production, thereby increasing population movement to lower elevations and exposure to intense malaria transmission. These two events are believed primarily responsible for the dramatic increase in human infections and infectious reservoirs present in the highlands during the outbreak period. This investigation further underscores the importance of malaria and its impact on presumed NAI deficient highland populations. Despite the circumstantial nature of these conclusions, malaria did increase dramatically in the highlands, with environmental, biological and social factors all likely playing large roles in its devastating dissemination.

Malaria disease presentation

In late September 1997, active health surveillance indicated that malaria was prevalent in the highlands. Unsupervised mass antimalarial drug administration (chloroquine phosphate) was begun shortly afterwards and distributed to as many accessible communities as possible. By early November, the reported number of deaths had waned considerably, reaching near normal rates based on district health statistics. Although, multiple etiologies and other concomitant causes of severe illness could not be definitively excluded, clinical and epidemiological evidence, along with multiple site survey data, strongly implicated malaria as the primary cause of the excess morbidity and mortality at elevations between 1,000 and 2,000 m. During the same period (late September-early October), unusually high rates of morbidity and mortality attributed to *P. falciparum* (>75% of diagnoses cases) were being reported in the Ok Tedi Mining area (Tabubil), a highland site (>1,000 m) in PNG near the border with Irian Jaya (J Hii, personal communication, 1998). Reported cases increased from 260 in September to over 900 in October with a sharp increase in severe malaria referred to the local health center. Similar 'dry season' outbreaks of malaria have occurred recently in the mine area during 1986 (an El Niño year) and 1990.

Many of the reported causes of death in 1997, ranging from "meningitis" and "influenza" as severe forms of falciparum malaria, and "dysentery and severe diarrhea" as various intestinal syndromes associated with severe malaria, have commonly been reported initially as 'causes' of other highland malaria epidemics (Peters *et al*, 1958; Garnham, 1948). Moreover, three of the category conditions recorded as cause of death in 1997- diarrhea, ARI and pneumonia, form a part of the broad syndrome of severe malaria. An independent investigation conducted in the first quarter of 1998 in the Jayawijaya District arrived at a similar conclusion, that malaria had increased considerably in the district and was most likely responsible for the majority of the deaths (Cooper, 1998).

Clinical cases compatible with severe malaria are believed due, in large part, to the relatively low level of naturally acquired immunity (NAI) to malaria in these highland populations (Baird, 1998) and the predominance of *Plasmodium falciparum* infections. The relatively low AES among highland populations support this conclusion. Characteristically, severe malaria caused by *P. falciparum* is generally the most prevalent diagnosed species during highland epidemics (Garnham, 1945; 1948; Peters and Christian, 1960). Because of the deficient NAI, disease severity and death rates in highland communities generally increases with elevation. The population's compromised nutritional status may have further exacerbated disease symptoms and outcomes because of acute shortages of staple foods created by the drought as witnessed in Africa (Fontaine *et al*, 1961).

Signs and symptoms of malaria are extremely variable and can resemble that seen in the early stages of many illnesses associated with abrupt onset (Benenson, 1995). In particular, severe disease caused by *P. falciparum* can present with a quite varied picture including fever, cough, respiratory distress, headache, diarrhea. Pneumonitis, respiratory distress (acidosis) and bronchopneumonia are not uncommon concomitant findings with complicated cerebral or other forms of severe malaria (Edington and Gilles, 1974; Gilles, 1988). Coma leading to death can often exceed 10% in untreated cases in children and nonimmune adults. The association of diarrhea with malaria is of importance as many malaria outbreaks are initially reported as diarrhea, dysentery, or other enteric conditions. The leading cause of death between August and October 1997 was reported as ARI. This is not a surprising given that chronic bouts respiratory disease are common in the highlands. Malaria could presumably exacerbate concurrent respiratory problems in these populations. The reasons for the relatively larger number of 'ARI-related' deaths in adults (>35), particularly males, is unclear. Studies carries out in Africa had identified adult males at greatest risk for disease because they traveled to endemic areas more often (Van der Stuyft *et al*, 1993). A more intriguing possibility is based on age-related differences of immune response observed in nonimmune populations newly exposed to acute *P. falciparum* infections, in which there appears to be an exaggerated susceptibility of adults to severe morbidity and mortality compared to children (Baird, 1998).

Highland malaria outbreak settings

The sudden and nearly simultaneous occurrence of reported sickness and death over a wide area marked the height of the outbreak. Similar dramatic malaria outbreaks, sometimes lasting only several months, have been described from the highlands of East Africa and elsewhere (Garnham, 1945; Mouchet *et al*, 1998). The 1955 malaria epidemic in the Mt Hagan area (~1,600 m asl) of PNG was believed to have 'suddenly' flared up because of a gradual increasing incidence of undetected malaria being clinically misdiagnosed as influenza or dysentery (Spencer *et al*, 1956). A dramatic and similar finding of fulminant malaria was seen in the 1934-35 Sri Lanka epidemic, and was attributed to a sudden unexplained increase of undetected malaria relapses followed less than one month later by an abrupt outburst of primary infections (Gill, 1936).

The 1997 outbreak is not an unprecedented event in Irian Jaya. A strikingly similar outbreak took place in May 1958, wherein nearly 16 per 1,000 population reportedly died during a malaria epidemic at elevations ranging from 1,600 to 1,900 m (Metselaar, 1959). This 1958 epidemic was associated with notable drought conditions during an ENSO period. He postulated that both increased available vector larval habitats and higher ambient temperatures contributed to this short-lived outbreak. Mass chloroquine and pyrimethamine were subsequently distributed and the epidemic was quickly abated. Before 1997, the last major drought to adversely affect Irian Jaya was during the 1982-83 El Niño (Webster and Palmer, 1997). Anecdotal evidence during that period indicates that severe illness and excess mortality were common. Unfortunately, health investigations during or immediately after the 1958 episode were not conducted.

Area delimited and isolated focal outbreaks of malaria, under favorable conditions (*eg*, increased vector larval habitats, rainfall and temperature), are considered occasional, periodic events in highland locations (Garnham, 1948; Lindsay and Martens, 1998). The principal climatic factors influencing transmission are rainfall and temperature. Highland epidemics have been often associated with periods following unusually high levels of rainfall (Garnham, 1948; Peters and Christian, 1960, Mouchet *et al*, 1998; Lindsay and Martens, 1998) and periods of climatic warming (Loevinsohn, 1994). Far more unusual, are instances of drought-related malaria as experienced in highland New Guinea (Metselaar, 1959; Van Dijk and Parkinson, 1974). Periodic malaria epidemics not uncommonly occur in ENSO-affected areas (Bourne *et al*, 1994). The extraordinary increase in malaria and associated deaths in 1997 was indirectly associated with the prolonged and severe drought created by the intense ENSO affecting the Australasian region.

Increased malaria coincided with a period of a dramatic deficit in precipitation, increased air temperatures and barometric readings. From August to November 1997, a 75% and 70% overall reduction in normal (1973-96) rainfall and rain days, respectively, was recorded. A marked reduction in the 'wetness index' reflected the reduced amount and distribution of rainfall during the drought months compared with means from previous years. The temporal distribution of rainfall is as critical a component to *An. punctulatus* abundance as is the amount of rainfall. As normal larval habitats became rare, drying stream beds would have provided acceptable alternatives (Van Dijk and Parkinson, 1974).

Climate and vectors

Past epidemics in the New Guinea highlands have been linked to increases in mosquito longevity and sudden increases in vector populations (Peters and Christian, 1960). In late July, as rainfall rapidly decreased, many temporary pools of standing water formed along stretches of steep gradient streams. Such streams, during years of normally plentiful rainfall, are associated with fast-flowing water that is unsuitable as anopheline larval habitats. This transitory pooling likely permitted sufficient and rapid increases in vector mosquito populations that presumably could sustain recently introduced or intensify local low-level malaria transmission. Moreover, gardens used for food production are normally near streams at lower altitudes below hillside villages. Villagers will often sleep close to gardens in the evening to protect cultivated sweet potatoes from wild pigs, possibly increasing risk of malaria exposure.

The members of the *Anopheles punctulatus* complex are the primary vectors of malaria in New Guinea (Van Dijk and Parkinson, 1974). This species has been incriminated as an important malaria vector in the Irian Jaya (Bangs *et al*, 1996) and PNG (Spencer *et al*, 1956) highlands. *Anopheles punctulatus* larvae were identified from temporary aquatic habitats in several malaria affected communities surveyed. This heliophilic species prefers small, temporary shallow sunlit collections of water for larval habitats. Under optimal conditions, synchronous larval development can be completed within 6-9 days time, producing a rapid increase in population numbers (Charlwood, 1985). Moreover, this opportunistic species can easily invade previously vacant areas (Charlwood *et al*, 1986). During this investigation, adult mosquito collections (Irian Jaya Department of Health, unpublished data, 1997) routinely resulted in very low human-biting densities, a common characteristic of this species (Charlwood, 1985). Nevertheless, *An. punctulatus* has been proven an efficient vector at very low biting densities in other highland locations in Irian Jaya (Bangs *et al*, 1996). Because of the continuing drought, we surmise the natural reduction or elimination of mosquito larval habitats in stream beds contributed to the eventual decline of new malaria cases.

Some contributing factors to the outbreaks

Environmental, biological and socioeconomic factors, may play a role in changing malaria rates in unstable zones of transmission. Human-influenced environmental changes, such as human migration, rapid expansion of cultivated land, irrigation practices, and deforestation have been linked to increased highland malaria in Africa (Mouchet *et al*, 1998; Lindsay and Martens, 1998). With the exception of increased migration during periods of famine, these other factors have been minimal in the most malaria-affected areas of Irian Jaya and are unlikely to have contributed to the increases in severe malaria in 1997. Abandoned fishponds have been considered a possible link to increased anopheline populations and transmission in the highlands; however, many of the affected areas lacked fishponds.

Reservoirs of *Plasmodium* parasites during the Irian Jaya highland outbreaks were of two possible origins; introduced cases and persistent local malaria infections maintained through relapse or recrudescence. Under normal circumstances, individuals or small groups of people will occasionally venture to lower elevations along or below the mountain fringe zones (300-1,000 m asl) to garden, collect raw materials and barter. Understandably, some people would contract malaria in these locations and return to the highlands infected as has been described from Irian Jaya and PNG (Metselaar, 1959; McMahon, 1974). During the drought period, the grave water and food shortages in the highlands contributed to increased demographic movement to lower elevations associated with intense malaria transmission. This increased exposure would have thus compounded the prevalence of human infections and infectious reservoirs in populations returning to the highlands. Between August and October 1997, gametocyte rates and densities for *P. falciparum* from community-based blood slides were high, ranging from 25 to 49%. During a similar highland epidemic in 1958 in the Kemaboe Valley in the Jayawijaya District, the *P. falciparum* gametocyte rate was greater than 58% (Metselaar, 1959). By comparison, gametocyte rates (all species) in the highlands of PNG during periods of low endemicity have been reported below 2% and during epidemic periods would increase to >5% (Peters and Christian, 1960).

It is interesting to postulate the influence that ENSO patterns may have had on malaria recurrences in the highlands. The reasons precipitating malaria relapses and recrudescences are unclear and could involve the cooler temperatures, a drop in air pressure or stress during stays in the highlands (Lindsay and Martens, 1998). In Africa, travelers from the lowlands have experienced relapses and recrudescences upon entering higher elevations (Garnham, 1948). Sudden drops in temperatures have been linked to increases in apparent malaria relapses and gametocyte carriers in tropical lowlands (Muirhead-Thomson and Mercier, 1952).

How important malaria importation verses local transmission contributed to the overall number of cases in the highlands during 1997 is not known and is currently an area of urgent investigation. However, the unusually high percentage of the population symptomatic, among all age groups, strongly suggested some degree of local transmission took place at these higher elevations (Molineaux, 1988; Russell *et al*, 1963; Peters and Christian, 1960). This suspicion was further supported by the presence of *P. falciparum* circumsporozoite protein (*ie*, sporozoites) found in *An. punctulatus* captured at approximately 1,700 m in the outbreak area. The decreased rainfall and reduced cloud cover during the outbreak period would have resulted in more insolation reaching the exposed terrain. Above an elevation of 1,500 m, marked differences in temperature are conspicuous between sunshine and shade, wind and calm (Trewartha, 1954). Higher daytime temperatures may have played a part in accelerating the completion of the parasite's extrinsic incubation (latent) cycle in the vector. Depending on the authority, the minimal conservative estimates required for successful sporogony varies from 15-17.5°C for *P. vivax* to 18-20°C for *P. falciparum* (Molineaux, 1988; Boyd, 1949). At or below these average temperatures can indefinitely delay completion of the latent cycle, and above the minimum temperature the incubation period decreases exponentially with increasing temperature (Russell *et al*, 1963).

Ambient temperature controls a delicate balance between required time for extrinsic parasite development and vector longevity required for successful transmission. Depending on the preferred vector microhabitats, such as resting sites of the adult mosquito (*eg*, inside houses versus outside), the lower than normal outside evening temperatures could have counteracted the daytime increases. During August and September the average increased diel ambient air temperatures were only slightly below normal. However, inside dwellings, where some vectors may rest, the temperatures can be 2-5°C higher than outside (Garnham, 1945). In Oksibil, Irian Jaya (1,260 m asl), indoor temperatures have been found 2-4°C higher (MJ Bangs, unpublished data, 1997). These differences in outside *vs* indoor temperatures are considered important in the transmission of malaria at higher altitudes (Garnham, 1948). A basic epidemiological simulation model (Lindsay and Martens, 1998) would indicate the difference of only 3°C, from 17° to 20°C, is sufficient to provoke an epidemic. Additionally, anopheline longevity, on average, is of greater duration at higher altitudes than the lowlands of New Guinea (Peters and Christian, 1960), which can offset the prolonged incubation period of parasites in cooler climates. This is especially evident in highland localities where significant levels of *P. malariae* (long latent period) transmission occurs (Bangs *et al*, 1996).

Post-outbreak reflections

Clearly, the overall incidence of severe disease and related death in the highlands was far above expected levels. However, the complete number of deaths and full extent of the 1997 outbreak is not known because of inadequate reporting and lack of comprehensive investigations in many sites. Despite the prevailing drying influence of the ENSO, not all areas appeared to experience increased malaria. Differences between localities in terrain, spatial heterogeneity in climatic patterns, variations in available larval habitats and vector abundance, vector feeding behavior, and human factors likely influenced disease occurrence. The clustering, focal nature of outbreaks in the highlands of East Africa is well recognized (Lindsay and Martens, 1998). Although this event would be classified an 'epidemic', epidemiologically, the requisite baseline and comparative retrospective health statistics are lacking from most remote areas in the highlands, further complicating the interpretation and magnitude of what actually occurred.

These epidemiological findings were subject to several limitations not uncommon for remote locations suffering from acute disasters and poor infrastructure (Wetterhall and Noji, 1997). Principal among them was the nonstandardized data collection and time-lags in reporting information to the local health department by the many multilateral health groups. Epidemiological parameters, including accurate disease-specific morbidity/mortality data was limited and often anecdotal, precluding reliable case fatality rate estimates. In some cases, data collection was subject to observation and convenience sampling bias. Human factors, such as population movement, could not be closely monitored in these isolated groups. Site-specific climate data was not available from the multiple outbreak areas. The Wamena station located at around 1,600 m was the only source of comprehensive climate data in the highlands and was considered an adequate substitute when measuring general climatic trends only. The relative contribution of location (*ie*, lower *vs* higher elevations) for contracting malaria could not be clearly established. Lastly, many of the problems encountered were related to severe constraints in travel and communication in the highlands. During the investigation period, transport was very limited and prioritized for provision of food to the drought-affected areas. This greatly hampered attempts to acquire timely site-specific health information. Nevertheless, we felt this event merits reporting to the greater health community, illustrating further some of the inherent problems associated with conducting disaster outbreak investigations under difficult situations. Similar issues and conclusions have been drawn from many of the experiences in the East African highlands (Lindsay and Martens, 1998).

Present and future malaria

The August and September outbreaks have produced great alarm because of the wide regionalized extent of malaria in these very remote areas. The culmination of many simultaneous and isolated events clearly overwhelmed the local health care and control capabilities. As far as known, indoor residual spraying with insecticides had never been attempted in the highlands and the logistics required for adequate and sustained coverage are presently not available. This event further underscores the importance of malaria and its impact on vulnerable, presumed NAI deficient highland populations. An underestimation of the importance of malaria at higher elevations has commonly led to oversights misidentifying the cause of illness and delayed appropriate remedial action (Garnham, 1948; Spencer *et al*, 1956). To illustrate, a recent report on an outbreak in late 1995 of apparent severe acute respiratory illness (as "probable influenza A virus infection"), associated with significant morbidity and high mortality (>300 deaths), occurred in the same general locality of Irian Jaya as the 1997 outbreak described herein (Corwin *et al*, 1998). However, the interpretation appears compromised for not addressing the possibility of malaria as a precipitating cause in the 1995 outbreak. Finally, the association of ENSO-related and other climatic anomalies that can result in periodic heightened malaria exposure and transmission is illustrative of how changing local meteorological events can dramatically alter disease patterns in a short amount of time (Boume *et al*, 1994; Lindsay and Birley, 1996).

Despite the return of the rains in December 1997, the general weather patterns remained unsettled in highland New Guinea. Medicins Sans Frontières (MSF) and other health groups continued to report alarming levels of malaria and death in the highlands far into 1998 (MSF, unpublished data, 1998). Critical issues of disease surveillance and control in the highlands remains a serious concern. Simple and early diagnoses and prompt treatment of disease in isolated populations is a daunting, near impossible task. Demographic growth due to expected migration of labor and increases in average life expectancy commensurate with increased available health care in the highlands will influence future disease patterns. We predict communicable disease outbreaks, including malaria, will likely increase in frequency in the Irian Jaya highlands as socioeconomic development and population numbers and movement increase (Anthony *et al*, 1992; Radford *et al*, 1970). Predicted global climate change has suggested scenarios of increased malaria risk (Patz *et al*, 1996) and seasonal epidemics at higher altitudes (Jettsen *et al*, 1996). It may be possible that remote sensed data and accurate meteorological forecasts many months in advance may provide powerful predictive methods of disease outbreak risk in New Guinea (Molyneux, 1997). However, at this stage, much more work is needed before it will be possible to develop predictive capabilities of forecasted and monitored climates in the highlands. Examples of analysis of retrospective malaria data have failed to show a strong relationship of rainfall and malaria incidence in the dry zone of Sri Lanka (Van der Hoek *et al*, 1997). Similarly, the average temperature increase of 0.5°C during the previous two decades in Africa had not been incriminated as the major reason for the changes in malaria incidences in the highlands of Kenya and Madagascar (Mouchet *et al*, 1998). Clearly, the social and biological factors involved, together under the influence of changing environmental conditions, are presently difficult to assess in predictive modeling (Molyneux, 1997).

There are striking similarities, both in circumstances and epidemiological explanations, between New Guinean and East African highland malaria (Lindsay and Martens, 1998). However, a tremendous amount remains unknown about highland malaria in Irian Jaya and much remains conjectural on the epidemiology of outbreaks at these higher elevations. Carefully designed field studies are needed to understand the ecological and epidemiological dynamics and importance of highland malaria transmission. In line with the basic elements of the Global Malaria Control Strategy endorsed by the World Health Assembly in 1993 (Trigg and Kondrachine, 1998), longitudinal investigations in Irian Jaya are beginning in order to define the unstable nature of the host-vector-parasite relationships in relation to climate, elevation and human factors that affect these vulnerable communities.

Better epidemiological knowledge and the development of a coordinated, prospective approach to health surveillance will significantly strengthen disease detection, prediction and outbreak response in the remote, logistically difficult areas of Irian Jaya. Specifically, highland sentinel sites have been identified based on ability to provide periodic and sustainable information gathering on basic health, population movement and climatic indices. After training, sites will be able to perform more definitive malaria diagnoses (use of rapid dip-stick methods and/or standard microscopy) and be capable of forwarding standardized data collection weekly (by radio) to the district health center for recording and analysis. Follow-up reporting to sentinel sites and periodic refresher training will be mandatory for sustainability of the program. Additionally, vector studies are urgently needed to assess the relative importance of transmission at higher elevations, provide direct evidence of the species involved, and design appropriate strategies for transmission control during interepidemic and epidemic periods. In general, malaria and vector surveillance will form an important component to the overall disease surveillance and outbreak response capabilities being implemented in Irian Jaya.

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