J Vector Borne Dis 56, September 2019, pp. 179–188

Review Article

Malaria in Sri Lanka: Investigating causes of the recent elimination and making plans to prevent reintroduction

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ABSTRACT

Sri Lanka is a country that has long suffered from epidemics of malaria. In this historical context, it is remarkable that in 2016 the Indian Ocean island nation was able to officially celebrate the elimination of this parasitic disease of major public health importance. The most devastating outbreak recorded in Sri Lanka was during 1934–35, when close to 80,000 human deaths were reported. Indoor residual spraying with the insecticides, DDT and malathion commenced in 1947 and was successful in causing a rapid decline in malaria incidence. However, poor vector control measures, resistance of mosquitoes to these insecticides and resistance of blood-stage *Plasmodium* parasites to the prevailing drugs used are considered the principal reasons for the occurrence of subsequent outbreaks. Despite this, Sri Lanka achieved the significant milestone of zero locally transmitted malaria cases in October 2012 and zero recorded deaths since 2007. Vector surveillance, parasitological examination, and clinical case management were collective effective activities that most likely led to elimination of malaria. Yet, there remains a high risk of reintroduction due to imported cases and an enduring vulnerability to vector transmission. In order to prevent re-establishment of malaria, continued financial support, sustained surveillance for vector species present in Sri Lanka and effective control of imported cases through rapid detection and early diagnosis are all required. In addition to these immediate practical priorities, further studies on vector biology and genetic variations that affect vectorial capacity would help to shed light on how to avoid reintroduction. This review affords an insight into the determinants of past malaria epidemics, strategies deployed to achieve and maintain the current status of elimination, lessons learnt from this success and plans to avoid resurgence of infection.

Key words Elimination; importation; malaria; *Plasmodium;* Sri Lanka; vector

INTRODUCTION

Malaria is one of the most important and life-threatening infectious diseases in the world. In 2018, the latest year for which information is available, an estimated 228 million clinical cases of malaria in humans occurred worldwide, resulting in approximately 416,000 deaths[1]. Of all reported incidence, 93% of malaria cases and in excess of 390,000 deaths are from sub-Saharan Africa[1]. Within a general population, some groups are at high risk of contracting infection; these include pregnant women, infants, children <5 yr of age, patients with HIV, non-immune migrants and travelers[1–2].

Sri Lanka, a small island of 65,525 km^2 in area located in the Indian Ocean, is a country that has a long history of epidemic malaria[3]. Since record-keeping started several centuries ago, this has had a major public health impact on the resident population, which currently stands at 22 million (*https://www.indexmundi.com/sri_lanka/demographics_profile.html*). However, from the turn of the 21st century, the reported incidence of malaria declined progressively as a consequence of a concerted campaign of entomological surveillance, parasitological examination, and improved clinical case management[3]. Yet, the exact cause of this sudden reduction in malarial disease spread is unknown. This review provides an insight into the recent research performed to gain a better understanding of this phenomenon, concluding by discussing how this knowledge may be applied to combat malaria in a global context.

Parasite and vector species

The aetiological agents of malaria are protozoan parasites of the *Plasmodium* genus. Of more than 250 species that are known to infect vertebrates, only six species are recognized as responsible for regularly infecting and causing disease symptoms in humans, *viz. Plasmodium falciparum, P. vivax, P. malariae*, *P. ovale curtisii*,

P. ovale wallikeri and *P. knowlesi*[4–5]. In Sri Lanka at any time in history, only three of these species, namely *P. falciparum*, *P. vivax* and *P. malariae*, have been identified as the cause of disease outbreaks[3].

Female mosquitoes of the genus *Anopheles* act as vectors for transmission of malaria. There are approximately 430 *Anopheles* mosquito species found worldwide but only 30–40 of these transmit malaria. The identity of transmitting species varies depending upon the geographical region and the environmental conditions[6]. There are 23 reported *Anopheles* species in Sri Lanka[7]. Other than the principal vector *An. culicifacies*, three species are considered to be possible vectors; *An. subpictus*, *An. varuna* and *An. annularis*[8–9]. However, in 2015 and 2017, respectively, two new *Anopheles* species, *An. jeyporiensis* and *An. stephensi*, were discovered in the country[10–11]. Due to a lack of availability of mosquito surveillance information in Sri Lanka prior to 2010, it is unclear whether or not these two species have gone undetected on the island over the past few decades or if their recent detection is indicative of a recent invasion[10–11].

Malaria: Historical significance

Sri Lanka experiences a tropical climate. For the purpose of studying malaria, the country has been divided into three distinct climatic zones[12]; dry, intermediate and wet (Fig. 1). The wet zone receives a relatively high mean annual rainfall of over 2,500 mm, due to the southwest monsoons from April to June, while the dry zone receives a mean annual rainfall of less than 1,750 mm, mostly through the northeast monsoons from October to January. The intermediate zone receives a mean annual rainfall of 1,750–2,500 mm. When malaria was prevalent, endemicity varied by climatic zone and was determined primarily by the local habitats of *An. culicifacies*[8]. The disease was endemic across the entire dry zone and a greater part of the intermediate zone. During excessively dry weather there were outbreaks or epidemics in the wet zone[12]. Only the high hill country was entirely free from malaria as the low overnight temperatures were not conducive to mosquito survival.

Major outbreaks recorded in Sri Lanka

1934–1935: The epidemic that started towards the end of 1934 and continued until April 1935 was the most devastating outbreak of malaria in Sri Lanka on record (Fig. 2). An unusually prolonged drought across the entire island led to the formation of riverine pools. The resultant expansion of habitats for pre-imaginal development of the principal vector *An. culicifacies* was implicated as the major factor in the extended range and intensity of this epidemic[13].

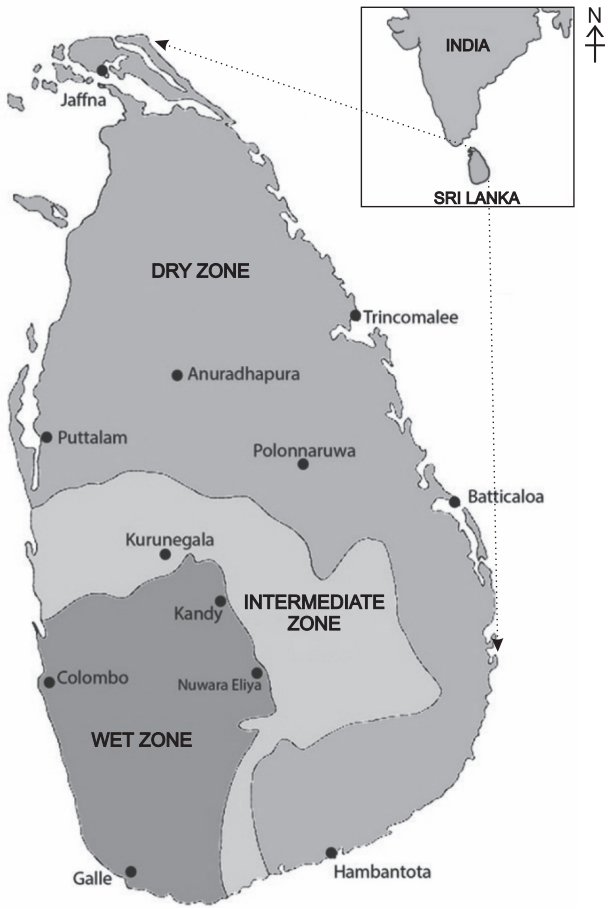

Fig. 1: Climatic zones of Sri Lanka[14] based on annual rainfall.

It is estimated that a total of 5 million individuals were infected, of whom nearly 80,000 died[13–14]. Throughout the epidemic, *P. vivax* was the predominant parasite (*P. vivax* 62.2%, *P. falciparum* 36.7% and *P. malariae* 1.1%)[12]. Of anopheline mosquitoes collected from epidemic areas, 88.5% were *An. culicifacies* and 8.7% were *An. subpictus*. The highest infection rate was observed in December 1934, ranging between 10.8–14% of the population of geographically separate regions[12].

1967–1968: Following the introduction of the insecticide, dichlorodiphenyltrichloroethane (DDT) in 1946 for indoor residual spraying (IRS), malaria morbidity and mortality declined steadily. After widespread use of DDT over several years, in 1963 the annual incidence reached a low of 17 (with only six indigenous cases) and for the first time Sri Lanka stood on the verge of eliminating malaria. However, the then Sri Lankan government made what hindsight shows to be a catastrophic mistake by loosening vector control measures and disbanding DDT spraying teams. Within months' malaria incidence started to increase, culminating in an island-wide re-emergence in 1967–1969, with over 50,000 clinical cases recorded in

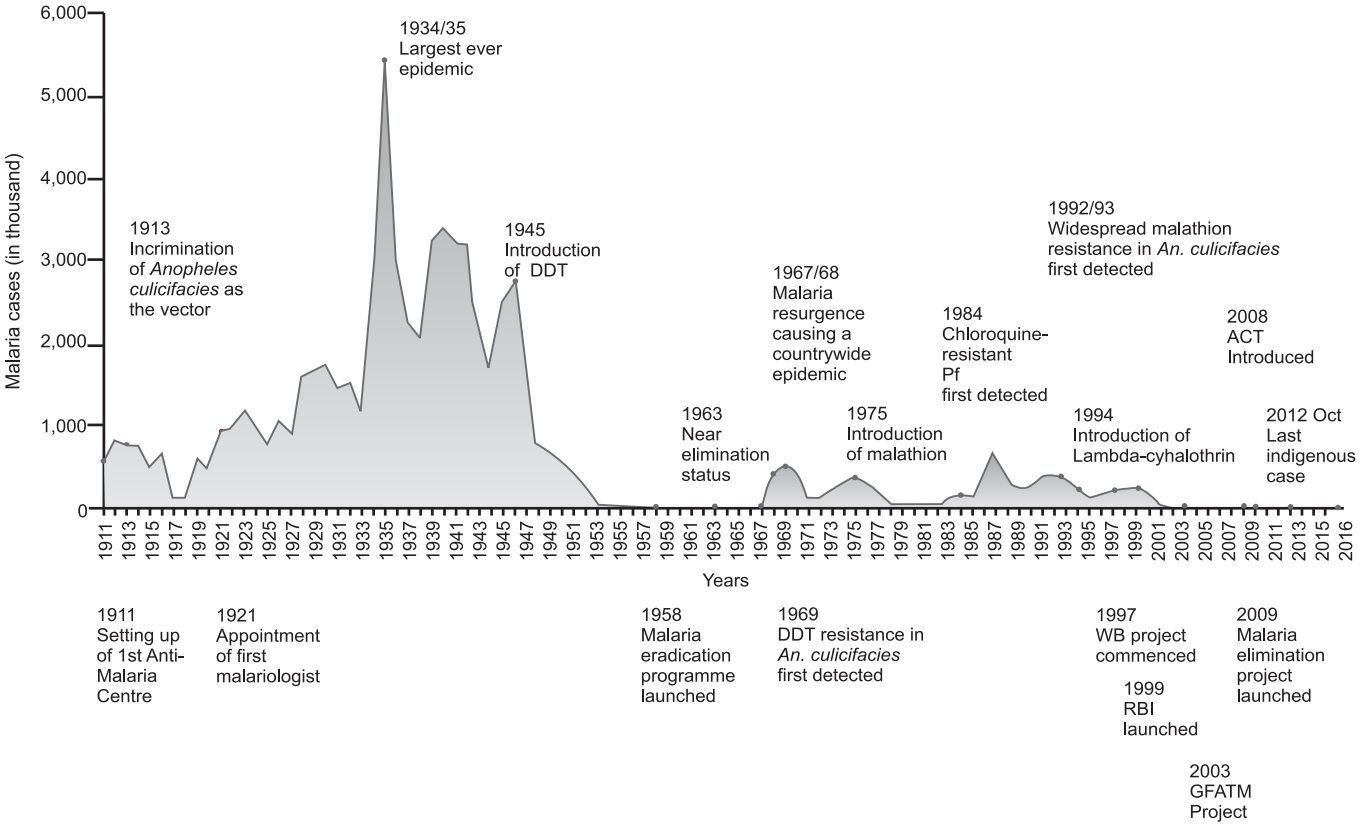

Fig. 2: Malaria cases in Sri Lanka, 1911–2016 (*Source:* Anti-Malaria Campaign, Ministry of Health, Sri Lanka & WHO Regional Office for South-East Asia, 2017; Available at: *http://apps.searo.who.int/PDS_DOCS/B5395.pdf*).

1969 (Fig. 2). Yet, fortunately only 58 deaths eventuated because 99.9% of the infections during this time were due to *P. vivax* rather than to the more virulent *P. falciparum*[12].

At the end of the 1960s, it became evident that resistance of mosquito vectors to insecticides and resistance of malaria parasites to chemotherapeutic drugs presented significant barriers to the success of malaria elimination programmes[15]. In 1969, DDT resistance was discovered for the first time in Sri Lanka[14]. As a resolution to this problem, in 1977 the country switched to use of the unrelated malathion. Despite initial promise, malaria incidence continued to rise during the 1980s. This was due to the emergence of chloroquine-resistant *P. falciparum*[16].

1980–2000: In the latter part of the 20th century, water irrigation schemes were expanded throughout Sri Lanka, thereby creating artificial breeding habitats for mosquitoes. The Mahaweli Project was a major development established in the country's climatic dry zone (Fig. 1) during this period. Due to resettlement programmes, people who previously lived in malaria non-endemic areas and thus lacked acquired immunity were relocated to endemic areas. It is thought that as a consequence these non-immune individuals were susceptible to the more severe manifestations of infection. As a result of this unfortunate occurrence, *P. falciparum* once again became a predominant species of malaria parasite on the island. In 1987 the *P. falciparum*: *P. vivax* case ratio[14] reached nearly 1:1. According to a study carried out on the Mahaweli Project, 93% of all anopheline mosquitoes collected in the project area were identified as *An. annularis*, previously recognized only as a vector of minor significance[17].

Current situation

Until the 21st century malaria was a significant public health concern in Sri Lanka, negatively affecting both the country's health and its economy. In the year 2000, there were 210,048 indigenous reported cases[16], but since October 2012 there has not been a single locally transmitted malaria infection and hence no indigenous deaths have occurred in the entire 5-yr period of 2013–2017 (Table 1). As levels of infection dropped, the proportion of reported indigenous cases that were caused by *P. vivax* and by *P. falciparum* changed over time (Table 2). After achieving three consecutive years of zero local cases, in September 2016 the World Health Organization (WHO) certified Sri Lanka to be free from malaria[1, 3]. However, malaria cases brought in from overseas by infected travelers continued

Table 1. Number of indigenous and imported cases of malaria reported during 2008–2017

Year	Total cases	Indigenous cases	Imported cases
2008	670	647	23
2009	558	531	27
2010	736	684	52
2011	175	124	51
2012	93	23	70
2013	95	0	95
2014	49	0	49
2015	36	0	36
2016	41	0	41
2017	56	0	56

Source: Annual Reports 2008–2017 Anti-Malaria Campaign, Ministry of Health, Sri Lanka.

Table 2. Percentage of malaria cases diagnosed as *P. vivax* and *P. falciparum* during 2001–2017

Year	% *P. vivax*	% *P. falciparum*
2001	84	16
2002	88	12
2003	88	11.4
2004	85	13.4
2005	92	5.8
2006	95	3
2007	96.4	3
2008	93	4.3
2009	95	3.8
2010	95.3	2.3
2011	90.3	6.8
2012	48.3	45.2
2013	54.7	44.2
2014	57.1	40.8
2015	47.2	47.2
2016	39	43.9
2017	29	25

For 2016 and 2017 the species of malaria parasite in some samples remains to be identified. *Source:* Annual Reports 2001–2017, Anti-Malaria Campaign, Ministry of Health, Sri Lanka.

to be identified[14]. While importation is at present the only source of malaria in the country, the existence of vector mosquitoes means that there remains a potential risk of reintroduction[18].

Possible reasons for the decline of malaria incidence

Parasitological examination: Examination to detect malaria parasites played an essential part in the case screening process. Passive case detection (PCD) is the screening of individuals attending health care institutions while active case detection (ACD) is a village-level screening of high-risk groups in endemic areas. This two-pronged screening approach facilitates efficient treatment regimens and informs tailored IRS programmes[19]. Activated passive case detection (APCD) is the mainstay of disease surveillance, which was a form of PCD used in Sri Lanka whereby all the fever cases were tested for malaria. In district hospitals, APCD capacity was enhanced in the last decade by doubling the number of trained microscopists compared to the late 1990s. For the years 1995, 2000 and 2005, this method helped in identifying 89.8, 89.4 and 94.0% of cases, respectively[20]. The diagnosis is heavily dependent upon the accuracy of microscopical techniques. The rapid diagnostic test (RDT) is another rapid method that was administered first in 2001 but is reserved for emergencies because of its high cost and limited availability.

Following the introduction of ACD in 1997, mobile malaria clinics have targeted conflict-affected, remote and inaccessible populations in all the regions of the island. The aim is to detect asymptomatic and symptomatic parasite carriers. RDTs are occasionally used in these clinics, but most tests are carried out by microscopy. The World Bank International Development Association and Global Fund supported ACD activities from 2003 onwards[20].

Entomological surveillance: In Sri Lanka, entomological surveillance served as a facet of the epidemic forecasting system and was an essential component in the national integrated vector management (IVM) strategy. The first entomological surveillance was instigated soon after the remarkable malaria epidemic of 1934–35 in order to attain early information on the possible occurrence of increased seasonal transmission and outbreaks. Trained officers were engaged in mosquito collection and it was their duty to gather anopheline larvae and adult mosquitoes from the breeding sites of *An. culicifacies* and dispatch these on a monthly schedule to the Central Malaria Laboratory for confirmatory identification[21]. In 1940, public health inspectors carried out a mandatory inspection of rivers and streams for larvae at both central and district levels. Data obtained from susceptibility tests and bioassays were used in planning IRS and the distribution of insecticide-treated nets (ITNs) and/or long-lasting insecticidal nets (LLINs). In 2009, a private organization, Tropical and Environmental Diseases and Health Associates, conducted entomological surveillance in targeted districts[20].

Vector control: The IVM approach was started in Sri Lanka during the 1970s, whereupon it contributed significantly to the reduction in malaria incidence. Strategies like IRS, ITN, LLIN, larviciding, filling abandoned

gem pits and intermittent flushing of canals and waterways formed part of this plan. In the late 2000s so-called 'field schools' were introduced with the aim of educating farmers about malaria vector management and the link between agriculture and public health[20].

In 1946 the primary vector control method of IRS was introduced nationwide. A spatial mosaic insecticide rotation was implemented in 1998, using a combination of up to six insecticides of the two classes, organophosphates and pyrethroids. The use of DDT was replaced by malathion in 1975 due to repeated reports of mosquito resistance to DDT. Lambda-cyhalothrin was introduced in 1994 and other novel insecticides were also used more recently. Spraying of pyrethroids was more popular among local communities than that of organophosphates as they emit less odour and do not leave a visible residue on house walls. In 2002, use of malathion ceased because of evidence of resistance[22]. National IRS coverage declined over a 15-yr period[20], from 64.8% in 1995 to 46.5% in 2000, then to 22.5% by 2005.

The widespread deployment of ITNs and LLINs was a second important vector control tool in Sri Lanka. The distribution of ITNs started in 1999 and LLINs were introduced in 2004 with the help of the Global Fund. In 2005, 14.8% of the population at risk was estimated to be covered by LLINs[22], which rose to 22.7% in 2009 and 34.6% in 2010.

The IVM brought the relevant stakeholders together and engaged local communities. This approach also harnessed vector surveillance research to best inform the use of insecticides and to determine the most satisfactory combination of vector control interventions and environmental management[20].

Case management: Appropriate patient management and effective treatment played a key role in achieving the successful elimination of malaria from Sri Lanka. Starting from the mid-1990s all the patients suffering from fever were tested routinely for malaria. However, since 2007 testing has been recommended only for febrile patients with malaria-related clinical history and symptoms. For Sri Lankan citizens traveling to malaria-endemic countries, chemoprophylaxis is provided for up to six months free of charge[20].

Chloroquine and primaquine were used to treat patients with *P. vivax* malaria. Typical dosages for adults were: chloroquine – 25 mg/kg body weight over 3 days; primaquine – 0.25 mg/kg per day for 14 days. The *P. falciparum* patients were treated with artemisinin-based combination therapy and primaquine. For severe cases, the use of intravenous artesunate or quinine dihydrochloride was introduced[23] in 2008 and updated[24] in 2014.

Cost of malaria elimination

The Sri Lankan government and the Global Fund were the principal financial contributors to the malaria control programmes[25]. Up to 2017, US$ 35.6 million from the Global Fund had been disbursed towards elimination efforts[26]. This has been used mainly to scale-up IRS, for active surveillance through mobile clinics, diagnosis and treatment, and for LLIN distribution[3, 26]. On the advice of the Ministry of Health, Nutrition and Indigenous Medicine (MoH), the Ministry of Finance allocated funding at a district level based on available resources and relative risk. The MoH's Anti-Malaria campaign (AMC)[27], supported by external funding and partnerships with non-government organizations, drove the decline in malaria incidence through adoption of innovative, evidence-based strategies of vector control, parasitological surveillance and clinical case management[20].

In 2014, the most recent year for which information is available, the entire budget allocated to the AMC for malaria control activities was US$ 934.1 million[26]. At that time, the median cost for malaria control at district level was US$ 195,316, with a cost per capita ranging from US$ 0.21–0.54. The overall estimated national cost per capita[3] was about US$ 0.50.

The AMC has identified nine key strategies to ensure malaria-free status and prevention of reintroduction of malaria to Sri Lanka. These strategies are under the following themes: (i) Strengthening services for surveillance for malaria case detection and protection of vulnerable population; (ii) Maintaining clinical skills, capacity and services for management of malaria cases; (iii) Strengthening outbreak preparedness, prevention and response to malaria outbreaks; (iv) Strengthening entomological surveillance and response through IVM; (v) Establishing a rigorous quality control system for malaria elimination; (vi) Strengthening information, education and communication (IEC) activities to raise awareness on the malaria elimination programme; (vii) Improving programme management and performance; (viii) Engaging in operations and implementation research; and (ix) Monitoring and evaluating programme performance. Table 3 shows the annual financial allocation for the 5-yr period between 2014–18 covering malaria elimination and prevention of reintroduction phases in Sri Lanka.

Implications for global health

Sri Lanka's long road to the successful elimination of malaria was troublesome and it took more than a century to achieve this ultimate goal. Nevertheless, despite this notable national accomplishment malaria remains a major global public health concern. Hence, important lessons

Table 3. Financial allocation of malaria elimination and prevention of reintroduction programme in Sri Lanka

Year	Capital budget (US$)
2014	8,819,615
2015	10,016,583
2016	9,205,899
2017	9,809,282
2018	10,220,913

Source: National Malaria Plan for Elimination Prevention of Sri Lanka 2014–2018. Anti-Malaria Campaign, Ministry of Health, Sri Lanka.

learnt from this experience can be applied to help control malaria in other countries and to prevent its reintroduction to Sri Lanka[14, 16].

The AMC's effective strategic plan was to intensively target both the parasite and the vector. Setting up mobile malaria clinics in areas of high transmission intensity was successful[27]. Incorporation of APCD, ACD and RDTs allowed a broad capacity for detection of parasites across the country. The genetic diversity and population structure of *Plasmodium* species have been estimated by investigating allelic variation of polymorphic microsatellite loci or candidate genes[16]. In order to identify the geographical origins of these parasites and to facilitate effective control and preventive measures, analysis of genetic maps of the parasites would be useful[29].

Effective vector control methods utilizing IRS, ITNs, LLINs and using larviciding chemicals and larvivorous fish have played a major role in malaria elimination[23]. An island-wide entomological survey and determination of vectorial capacities of *Anopheles* species in Sri Lanka should now be undertaken since there remains a threat from imported malaria cases. Studies of taxonomy, biology, ecology, behaviour and genetics of *Anopheles* mosquitoes will afford a better understanding of malaria vectors and their role in transmission[14]. These vector control measures can also reduce the transmission of other mosquito-borne diseases, notably dengue and chikungunya[30–31].

Public health system infrastructure

The Democratic Socialistic Republic of Sri Lanka, to give the nation its official title, provides free healthcare services in order to entrust health security, quality and modern healthcare facilities for all citizens and residents. The MoH has established a substantial free curative and preventive public health services network to enhance public health necessities provided by the Public Health Midwives, Public Health Inspectors, and the Medical Officers of Health/Divisional Health Officers. There are 593 government hospitals in the country that are staffed with ratios of 0.49 doctors and 1.93 nurses/midwives per 1000 population. Facilities are structured around primary care institutions and with secondary care institutions that provide specialized care[32].

The National Malaria Strategy in Sri Lanka focuses at central, provincial and district levels on the evolved consensus of stakeholders from the health and non-health sectors of government, the private sector, non-government organizations and international contributors. It comprises an evidence-based plan of action published/produced by the MoH and derived from the WHO Global Malaria Programme and South East Asia Regional Malaria control guidelines and recommendations. This ensures a coordinated, multilateral national response that aligns with the WHO malaria control strategy recommendations and reflects Sri Lanka's national development policies. The AMC plays a leading role in eliminating malaria and preventing its reintroduction through the provision of support to districts. In keeping with the National Health Sector Strategy, decentralization of implementation to the district level ensures that each district is directly responsible to provide funds and human resources for local community-based activities to combat malaria.

Current control strategies

The current approach to malaria elimination in Sri Lanka is based on strengthened surveillance, early reporting, case investigation and case management with a radical cure. A mechanism for reporting malaria cases in the private sector has also been established. An IEC programme targets at-risk populations. Other elimination strategies are also being developed or implemented, including border screening and treatment, formation of rapid response teams and a real-time malaria case information system.

The paradigm shift from malaria control to malaria eradication followed declarations at the Gates Malaria Forum in October 2007 and subsequent support voiced by the WHO[32], in response to which the board of the Roll Back Malaria (RBM) partnership and many other institutions renewed the inspiration for innovation and public health action. Very swiftly a coherent global action plan for malaria eradication was established and approved by the RBM partnership[34] in late 2008. This led to the formation of the Malaria Elimination Group (MEG), a consortium of scientists, public health decision-makers, control programme managers and funders. Based on all scientific evidence and case studies available at the time, the MEG compiled a guideline to policy makers for malaria elimination in areas that embark or have embarked on elimination strategies[35].

As part of the global campaign that started a decade

ago, the MoH, Sri Lanka launched a national malaria elimination programme in 2009 following an end to the civil conflict in the country. Funded in part by the Global Fund to fight AIDS, Tuberculosis and Malaria, the aim of the initial 5-yr drive was the phased elimination of malaria in the country by the end of 2014. This was achieved through the interruption of transmission of *P. falciparum* (by the end of 2012) and the interruption of transmission of *P. vivax* (by the end of 2014). There are three main partners in the ongoing project, namely the AMC, Tropical and Environmental Diseases and Health Associates Pvt. Ltd, and the *Sarvodaya Shramadana* Movement of Sri Lanka.

Among the current operational issues of concern to the programme are: sustaining political commitment for malaria elimination at national, provincial and district levels; maintaining adequate cadres in essential sectors to implement effective elimination and prevention of reintroduction nationwide; rehabilitation of primary care institutions in conflict-affected areas of the northern and eastern Provinces; and ensuring adequate infrastructure and logistical facilities for effective implementation. All these recent endeavours point to an ethical long-term pathway from control to elimination and eventually to eradication[36].

Ongoing challenges

There remain several challenges in sustaining interrupted transmission and preventing malaria reintroduction in Sri Lanka that are essential to consider in order to maintain the malaria-free status of the country. Development projects in the wake of the separatist war involve the presence of foreign national workers, particularly from China and India. The presence of such a large non-indigenous labour force increases the risk of imported infections, including malaria. Similar risks have been identified in association with illegal migrants[16, 37]. In addition, other movements of people to and from overseas elevate the risk of parasite carriage into the country. These include the posting of security force personnel previously engaged in United Nations peace-keeping missions in malaria-endemic countries and Sri Lankan nationals who travel to other countries in search of jobs, as tourists or pilgrimage visitors[16]. By contracting malaria outside Sri Lanka, these individuals could then reintroduce it to the country; this may reconcile reported imported cases with the presence of malaria vectors in early disease-endemic areas[38].

The identification of adult female anopheline mosquitoes is a central tenet of the malaria surveillance and control strategy enforced throughout the world. *Anopheles jeyporiensis*, a confirmed vector species for *P. falciparum* transmission in Vietnam and China, was detected after absence of 108 yr from Sri Lanka. Further, samples collected from coastal areas in the Mannar District of Sri Lanka presented some morphological features similar to *An. sundaicus* and *An. epiropticus*[7, 39]. Recent observations provided evidence of *An. stephensi* for the first time in Sri Lanka, from Mannar District[11]. Therefore, it is of paramount importance to investigate the presence of novel potential vectors for malaria transmission in early endemic areas. Hence, entomological monitoring procedures should be continued as a priority in order to maintain the WHO certification of malaria elimination from the island.

The bioecology of *Anopheles* breeding habitats in urban areas has received very little attention. Recent investigations have revealed, for the first time in Sri Lanka, the ability of *An. culicifacies*, *An. subpictus* and some other potential malaria vector species to breed in drains containing wastewater[40–41] and, like *Aedes* mosquitoes, in habitats with high salinity such as coastal brackish water[42–43]. Thus, adaptation of anopheline mosquitoes to breed in polluted water in urban locations could be a serious concern, especially given the fact that *An. stephensi* plays a major role in transmitting malaria in neighbouring southern parts of India[40].

Vectorial capacity provides a quantitative summary of the basic ecological attributes of a vector population in relation to parasite or virus transmission. A comprehensive study of the vectorial capacity of Sri Lankan anopheline varieties has not been performed for many years. Therefore, it is essential to study this aspect even though malaria cases are very low at present. This may facilitate an understanding of whether the decrease in reported incidence is due to a reduction of vectorial capacities among malaria vector species in Sri Lanka.

An effective surveillance and response system is an important part of a successful disease control programme. However, continued allocation of appropriate resources faces a challenge in view of the current absence of recorded malaria in Sri Lanka, with public funding prioritized for other more immediate public health concerns, notably dengue. Dwindling case numbers has meant that it is difficult to sustain the necessary level of interest within management, administration and field staff, and, more importantly, the required level of commitment from policy makers[16]. Consequently, meeting the substantial costs needed to maintain the country's malaria-free status is an increasingly demanding task, particularly since external funding has also reduced as the disease burden has fallen away. Under these circum-

stances, it may be a tough task to prevent the reintroduction of malaria to Sri Lanka as the majority of funds allocated to surveillance and control is currently met through limited local provision.

An international perspective

Malaria was officially eliminated from Sri Lanka[28] in 2016, yet there exists a potential risk of reintroduction due to imported cases of infection. Importation is the only source of malaria in the country today. Hence, screening, detection, early diagnosis of the disease and effective treatment are most important for preventing the possibility of a resurgence. There is evidence that *P. vivax* has the ability to re-emerge in regions where malaria eradication or control efforts in the past had apparently proved successful. Examples include Uzbekistan, Azerbaijan, South Korea and northern Afghanistan[1]. The decade following the end of the civil war that ravaged Sri Lanka from 1983 to 2009 has witnessed an expansion of social and economic development projects which led to an influx of imported hired labour from neighbouring malarious countries. There has also been a sharp rise in both immigration, principally from the Indian subcontinent, and international travel undertaken by residents and visitors. As a consequence, the risk of reintroduction of *P. vivax* into areas of Sri Lanka where species of *Anopheles* mosquitoes with proven vectorial capacity are present is considered to be high[29].

In October 2016, an imported case of infection with the zoonotic parasite *P. knowlesi* was reported from a Sri Lankan soldier returning from Malaysia[44]. As related monkey hosts and anopheline vectors are present in Sri Lanka, the development of local expertise to reliably identify zoonotic malaria parasites is a diagnostic laboratory training priority.

Chloroquine and primaquine have been the antimalarial drugs of choice in Sri Lanka over the past few decades[12, 23]. Sharing best practice in clinical case management with clinicians from other countries would be of great assistance to prevent the reintroduction of malaria in the nation. Research to unravel mechanisms of parasite resistance and to discover novel drug targets would benefit infection control nationally and globally.

DDT was first introduced as a front-line insecticide shortly after World War II but its continuous use over a long period prompted the emergence of resistant mosquitoes. On that account, research into susceptibility to insecticides and resistance mechanisms of *Anopheles* species are extremely important for ongoing maintenance of effective vector control[44]. Further studies relating to the vectorial capacity of malaria-transmitting anopheline species present in Sri Lanka and its genetic basis would provide insights into the means by which malaria elimination was achieved and help to prevent its reintroduction to the island.

The lack of indigenous cases of malaria in Sri Lanka since 2012 should be applauded. Yet, if the current absence of reported infections is extended for a longer period of time it may lead gradually to a loss of awareness among medical professions to the possibility of malaria as a clinical diagnosis. Other major vector-borne diseases, such as dengue and chikungunya, are transmitted by *Aedes* and not *Anopheles* mosquitoes[30–31]. With some justification, these are competing increasingly for limited public health services and management resources. However, the unexpected onset of major outbreaks of *P. vivax* and *P. falciparum* infections during the 20th century act as a warning that sustained surveillance and awareness among entomologists and medical professionals for malaria should be continued.

CONCLUSION

When considering the turbulent history of malaria in Sri Lanka and its recent elimination from the country, there are several strategies that have contributed to the recent rapid decline in case numbers. Notable among these is the implementation of methods for accurate parasitological examination, vigilant entomological surveillance and effective patient treatment. However, molecular level information relating to malaria infections is by itself not sufficient. The availability of more detailed genetic information about previous cases would be of immense value for further investigations and the rapid decline of malaria incidence.

Two species of *Anopheles* mosquitoes that have not been identified previously in Sri Lanka were recently found on the island. Therefore, a nationwide study of the vectorial capacity of all such mosquitoes is warranted. This type of investigation may not only shed light on the success of current measures to contain malaria but can also help to safeguard the country against the future reemergence of indigenous infections.

Ethical statement: Not applicable.

Conflict of interest

The authors do not have any conflict of interest to declare.

REFERENCES

1. World Malaria Report 2019. Geneva: World Health Organization 2019. Available from: *http://www.who.int/malaria/publica-*

tions/world-malaria-report-2019/en/ (Accessed on December 6, 2019).
2. Taylor-Robinson AW, Morley LC, Kane EG. Rationale for pregnancy-associated malaria vaccination predicated on antibody-mediated immunity to *Plasmodium falciparum* placenta-binding parasites. In: *Vaccines: Benefits and risks*. iConcept Press: Sunnybank Hills, Australia 2013; pp. 95–130.
3. Shretta R, Baral R, Avanceña AL, Fox K, Dannoruwa AP, Jayanetti R, *et al.* An investment case to prevent the reintroduction of malaria in Sri Lanka. *Am J Trop Med Hyg* 2017; *96*(3): 602–15.
4. *Malaria: Biology–Malaria parasites*. Atlanta, US: Centers for Disease Control and Prevention 2015. Available from: *https://www.cdc.gov/malaria/about/biology/parasites.html* (Accessed on May 16, 2018).
5. Ramasamy R. Zoonotic malaria – global overview and research and policy needs. *Front Public Health* 2014; *2:* 123.
6. *Malaria: Biology*–Anopheles *mosquitoes.* Atlanta, US: Centers for Disease Control and Prevention 2015. Available from: *https://www.cdc.gov/malaria/about/biology/mosquitoes/index.html* (Accessed on May 16, 2018).
7. Gunathilaka N. Illustrated key to the adult female *Anopheles* (Diptera: Culicidae) mosquitoes of Sri Lanka. *Appl Entomol Zool* 2017; *52*(1): 69–77.
8. Amerasinghe PH, Amerasinghe FP, Konradsen F, Fonseka KT, Wirtz RA. Malaria vectors in a traditional dry zone village in Sri Lanka. *Am J Trop Med Hyg* 1999; *60*(3): 421–9.
9. Yapabandara AM, Curtis CF. Vectors and malaria transmission in a gem mining area in Sri Lanka. *J Vector Ecol* 2004; *29*(2): 264–76.
10. Gunathilaka N, Hapugoda M, Abeyewickreme W, Wickremasinghe R. Appearance of *Anopheles jeyporiensis* James from Sri Lanka. *Med Entomol Zool* 2015; *66*(3): 121–5.
11. Dharmasiri AG, Perera AY, Harishchandra J, Herath H, Aravindan K, Jayasooriya HTR, *et al*. First record of *Anopheles stephensi* in Sri Lanka: A potential challenge for prevention of malaria reintroduction. *Malar J* 2017; *16:* 326.
12. Fernando P. Past malaria epidemics in Sri Lanka – An analysis. *J Coll Community Phys Sri Lanka* 2014; *19*(1): 27–41.
13. Briercliffe R, Dalrymple-Champneys W. Discussion on the malaria epidemic in Ceylon 1934–1935. *Proc R Soc Med* 1936; *29*(5): 537–62.
14. Wijesundere DA, Ramasamy R. Analysis of historical trends and recent elimination of malaria from Sri Lanka and its applicability for malaria control in other countries. *Front Public Health* 2017; *5*(5): 212.
15. Bruce-Chwatt LJ. Malaria and its control: Present situation and future prospects. *Annu Rev Public Health* 1987; *8:* 75–110.
16. Karunaweera ND, Galappaththy GN, Wirth DF. On the road to eliminate malaria in Sri Lanka: Lessons from history, challenges, gaps in knowledge and research needs. *Malar J* 2014; *13:* 59.
17. Ramasamy R, De Alwis R, Wijesundere A, Ramasamy MS. Malaria transmission at a new irrigation project in Sri Lanka: The emergence of *Anopheles annularis* as a major vector. *Am J Trop Med Hyg* 1992; *47*(5): 547–53.
18. Dharmawardena P, Premaratne RG, Kumudunayana WM, de AW Gunasekera T, Hewawitarane M, Mendis K, *et al.* Characterization of imported malaria, the largest threat to sustained malaria elimination from Sri Lanka. *Malar J* 2015; *14:* 177.
19. Disease surveillance for malaria elimination: Operational manual. Geneva: World Health Organization 2012; pp. 48.
20. Wickremasinghe R, Fernando SD, Thillekaratne J, Wijeyaratne PM, Wickremasinghe AR. Importance of active case detection in a malaria elimination programme. *Malar J* 2014; *13:* 186.
21. Gunaratna LF. Recent antimalaria work in Ceylon. *Bull World Health Organ* 1956; *15*(3-5): 791–9.
22. Beier JC, Keating J, Githure JI, Macdonald MB, Impoinvil DE, Novak RJ. Integrated vector management for malaria control. *Malar J* 2008; *7(Suppl. 1):* S4.
23. Abeyasinghe RR, Galappaththy GN, Gueye CS, Kahn JG, Feachem RG. Malaria control and elimination in Sri Lanka: Documenting progress and success factors in a conflict setting. *PLoS One* 2012; *7:* e43162.
24. Sri Lankan Ministry of Health Anti-Malaria Campaign 2014. General Circular No. 02-112/2014: Guidelines on malaria chemotherapy and management of patients with malaria. Available from: *http://amc.health.gov.lk/Circulars/Treatment-guidelines_Malaria.pdf.* (Accessed on May 18, 2018).
25. Abeyasinghe RR, Galappaththy GN, Smith Gueye C, Kahn JG, Feachem RG. Malaria control and elimination in Sri Lanka: Documenting progress and success factors in a conflict setting. *PLoS One* 2012; *7:* e43162.
26. Simac JN, Badar S, Farber JA, Brako MYO, Giudice-Jimenez RAL, Raspa SS, *et al.* Malaria elimination in Sri Lanka. *J Health Spec* 2017; *5*(2): 60–5.
27. Datta R, Mendis K, Wikremasinghe R, Premaratne R, Fernando D, Parry J, *et al.* Role of a dedicated support group in retaining malaria-free status of Sri Lanka. *J Vector Borne Dis* 2019; *56*(1): 66–9. doi: 10.4103/0972-9062.257778.
28. WHO certifies Sri Lanka malaria-free. New Delhi: WHO South-East Asia Regional Office 2016. Available from: *https://www.who.int/southeastasia/news/detail/05-09-2016-who-certifies-sri-lanka-malaria-free/* (Accessed on May 18, 2018).
29. Gunawardena S, Karunaweera ND, Ferreira MU, Phone-Kyaw M, Pollack RJ, Alifrangis M, *et al.* Geographic structure of *Plasmodium vivax*: Microsatellite analysis of parasite populations from Sri Lanka, Myanmar, and Ethiopia. *Am J Trop Med Hyg* 2010; *82*(2): 235–42.
30. Ali S, Khan AW, Taylor-Robinson AW, Adnan M, Malik S, Gul S. The unprecedented magnitude of the 2017 dengue outbreak in Sri Lanka provides lessons for future mosquito-borne infection control and prevention. *Infect Dis Health* 2018; *23:* 114–20.
31. Reller ME, Akoroda U, Nagahawatte A, Devasiri V, Kodikaarachchi W, Strouse JJ, *et al*. Chikungunya as a cause of acute febrile illness in southern Sri Lanka. *PLoS One* 2013; *8*(12): e82259.
32. Climate and health country profile – 2015 Sri Lanka. Geneva: World Health Organization 2015. Available from: *http://www.searo.who.int/entity/water_sanitation/srl_c_h_profile.pdf?ua=1* (Accessed on May 19, 2018).
33. Roberts L, Enserink M. Malaria. Did they really say...eradication? *Science* 2007; *318*(5856)*:* 1544–5.
34. Guerra CA, Gikandi PW, Tatem AJ, Noor AM, Smith DL, Hay SI, *et al.* The limits and intensity of *Plasmodium falciparum* transmission: Implications for malaria control and elimination worldwide. *PLoS Med* 2008; *5*(2): e38.
35. Lee PW, Liu CT, Rampao HS, do Rosario VE, Shaio MF. Pre-elimination of malaria on the island of Príncipe. *Malar J* 2010; *9:* 26.
36. *Anti-Malaria Campaign, Sri Lanka.* Research colloquium on 'Elimination of malaria from, and preventing its reintroduction to, Sri Lanka: Defining operational research properties'. Colombo: Sri Lankan Ministry of Health Anti-Malaria Campaign 2013.

37. Wickramage K, Galappaththy GN. Malaria burden in irregular migrants returning to Sri Lanka from human smuggling operations in West Africa and implications for a country reaching malaria elimination. *Trans R Soc Trop Med Hyg* 2013; *107*(5): 337–40.
38. Gunathilaka N, Abeyewickreme W, Hapugoda M, Wickremasinghe R. Determination of demographic, epidemiological, and socio-economic determinants and their potential impact on malaria transmission in Mannar and Trincomalee districts of Sri Lanka. *Malar J* 2016; *15:* 330.
39. Gunathilaka N, Hapugoda M, Wickremasinghe R, Abeyewickreme W. A comprehensive analysis on abundance, distribution, and bionomics of potential malaria vectors in Mannar district of Sri Lanka. *Malar Res Treat* 2019; *2019:* 1650180.
40. Gunathilaka N, Fernando T, Hapugoda M, Wickremasinghe R, Wijeyerathne P, Abeyewickreme W. *Anopheles culicifacies* breeding in polluted water bodies in Trincomalee District of Sri Lanka. *Malar J* 2013; *12:* 285.
41. Gunathilaka N, Karunaraj P. Identification of sibling species status of *Anopheles culicifacies* breeding in polluted water bodies in Trincomalee district of Sri Lanka. *Malar J* 2015; *14:* 214.
42. Surendran SN, Veluppillai T, Eswaramohan T, Sivabalakrishnan K, Noordeen F, Ramasamy R. Salinity tolerant *Aedes aegypti* and *Ae. albopictus*–Infection with dengue virus and contribution to dengue transmission in a coastal peninsula. *J Vector Borne Dis* 2018; *55*(1): 26–33. doi: 10.4103/0972-9062.234623.
43. Ranaweera AD, Danansuriya MN, Pahalagedera K, Gunasekera WKT, Dharmawardena P, Mak KW, *et al.* Diagnostic challenges and case management of the first imported case of *Plasmodium knowlesi* in Sri Lanka. *Malar J* 2017; *16*(1): 126.
44. Surendran SN, Jude PJ, Weerarathne TC, Karunaratne SP, Ramasamy R. Variations in susceptibility to common insecticides and resistance mechanisms among morphologically identified sibling species of the malaria vector *Anopheles subpictus* in Sri Lanka. *Parasit Vectors* 2012; *5*(1): 34.

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Received: 28 June 2018 *Accepted in revised form:* 5 June 2019