ARTICLES

EMERGENCY CONTROL OF *AEDES AEGYPTI* AS A DISEASE VECTOR IN URBAN AREAS

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ABSTRACT. Techniques for the emergency control of adult *Aedes aegypti* populations and their development are reviewed. Larviciding and environmental measures provide only delayed control of adult populations. Large-scale field trials of the ultra-low volume application of insecticide concentrates in Southeast Asia, South America and Africa, using aerial, ground, vehicle-mounted and hand-carried equipment, have, in most cases, resulted in satisfactory levels of control of adult populations. Sequential or indoor ULV applications of fenitrothion have provided immediate control and sustained reduction of the adult populations, often lasting well through normal peak transmission periods of dengue. Many ULV application trials in the Caribbean have not produced satisfactory control, but it is considered that this was due to the type of house construction, to the lower dosage rates of the malathion 96% ULV concentrates used, or to inappropriate droplet sizes. While ULV applications can provide rapid and effective emergency control of vectors at the time of outbreaks of disease in urban and periurban areas, they should not be used as a routine mosquito control measure nor as an alternative to reducing vector populations by environmental measures.

INTRODUCTION

The continued geographical spread and increasing incidence of *Aedes* (*Stegomyia*)-borne arboviruses is of much concern both to public health authorities and to the populations of the disease endemic areas. Deciding which techniques to use to control the principal vector, *Aedes aegypti* (Linn.), particularly during epidemic outbreaks, is an important problem for vector control organizations, and the choice of approach to take has been the subject of recent debate. This paper will review the spread of *Ae. aegypti*-borne disease and consider the options for its control, especially epidemic emergency control measures.

Dengue and its severe forms of dengue hemorrhagic fever and dengue shock syndrome (DHF/DSS) are rapidly spreading into new areas and, in Latin America, are appearing in countries where the vectors had been eradicated or under effective control. Dengue is now the arboviral disease that causes the greatest public health impact on man (Pinheiro 1989). It is likely that dengue and DHF will continue to spread to wherever the mosquito vectors are found in densities high enough to permit transmission of the causative virus.

The incidence of yellow fever (YF) has been increasing in recent years with outbreaks occurring in densely populated areas in Africa and the Americas. Although the vectors of yellow fever in rural Africa are species of the subgenus *Stegomyia* other than *Ae. aegypti* and in South America are species of the genus *Haemagogus*, all of the great urban epidemics of this disease on both continents have been transmitted by *Ae. aegypti*.

AEDES AEGYPTI-BORNE DISEASES, THE CURRENT STATUS

Yellow fever: While urban yellow fever in the Americas and, until recently, in Africa has not been reported for some years, the disease remains endemic on both continents. In 1988, 2,058 cases of yellow fever (YF) and 1,709 deaths, a case fatality rate (CFR) of 83.0%, were reported to the World Health Organization (WHO). The 3-year period, 1986–88 was extraordinarily active for YF, and the worldwide total of 5,395 cases and 3,172 deaths (CFR 58.8%) represents the greatest amount of YF reported to the WHO in any 3-year period since reporting began in 1948 (WHO 1990b). Many of the outbreaks and epidemics have occurred in close proximity to urban centers heavily infested with *Ae. aegypti.* Although transmission is usually by other species of mosquitoes in rural areas, *Ae. aegypti* was an important vector in recent yellow fever outbreaks in Nigeria (Nasidi et al. 1989); the 1987 outbreak was in a heavily populated area of 198 inhabitants/km^2 and was an urban type spread by *Ae. aegypti* (WHO 1987). The population at risk was estimated at 4 million, and it was estimated that some 116,000 cases with 24,000 deaths had occurred in Oyo State, Nigeria, though the number of cases officially reported was far smaller. The WHO 3-year review emphasizes the problem of underreporting. In 7 epidemiological studies undertaken of YF outbreaks over the last 25 years in Africa, morbidity and mortality were consistently under-reported by 10–500 times; the review concludes that during the period there were probably some 444,000 cases and 250,000 deaths in Nigeria rather than the far lower figures reported. Yellow fever patients are not infrequently treated in urban hospitals located in cities infested by vectors (Passos et al. 1982, WHO 1985). It can not be excluded that urban outbreaks of yellow fever will again occur. Concern about this is expressed by the WHO (1990c), as *Ae. aegypti* has now reinfested most of South and Central America, occupying habitats adjacent to areas where endemic YF transmission occurs. If the infectious agent is introduced into an urban cycle, *Ae. aegypti* transmission could occur as happened in Nigeria.

Despite the availability of a safe and effective vaccine for yellow fever since 1937 and efforts to vaccinate populations in exposed urban areas, the extent of the coverage, both in Africa and Latin America, is rarely satisfactory, nor are vaccination efforts always sustained by the authorities once the immediate threat of an epidemic passes.

Dengue and dengue hemorrhagic fever: Although considerable efforts are being made, no vaccine is yet available for the prevention of dengue, let alone DHF (Bhamarapravati et al. 1987, Marchette et al. 1990, Hoke et al. 1990). The development of a vaccine for dengue, and therefore DHF, is complicated by the existence of 4 serotypes of dengue virus. To prevent an immunoenhancement reaction leading to DHF, individual vaccines against all 4 serotypes, which would be quite impractical, or a polyvalent vaccine effective against all 4 serotypes would have to be available. Due to the large populations exposed, it is also essential that immunity conferred by a vaccine be long lasting if its use is to be economic. Considering the low levels of immunization achieved with the long-lasting yellow fever vaccine in Africa and Latin America, it is doubtful that a level of protection which would interrupt transmission could be achieved by vaccines.

There is no effective chemotherapeutic agent available for treatment of the illness caused by yellow fever, dengue or DHF; only supportive measures, usually in a hospital, can be applied to avoid mortality. The case fatality rate from DHF/DSS may vary from less than 1% to as high as 5%. Where adequate hospital facilities are available, treatment may save many DHF/DSS patients. However, the cost to the country of such large numbers of hospitalizations for intensive care treatment during epidemic outbreaks of DHF can be very great. The cost to Thailand of the large epidemic of DHF in 1987, with a reported 171,630 cases and 896 deaths (WHO 1989), for hospitalization, mostly of children 5–9 years old, is estimated to have been about US $16,000,000 (Ungchusak and Prayura 1988). An economic analysis of an epidemic of dengue fever was carried out in Puerto Rico in 1977 (Von Allmen et al. 1979). The cost of this epidemic, which lasted from July to December 1977, involving between 6.1 and 18.1% of the population, or about 355,000 persons, was calculated in terms of direct costs, e.g., medical care and epidemic control measures, and indirect costs as lost production of ill workers and parents of ill children. Indirect costs were estimated as $3.7–10.9 million, and the total cost of the epidemic was estimated to be from $6.0 to $15.6 million of which epidemic control measures comprised 7.8–20.2%. Kouri et al. (1989) reported that the economic impact of the 1981 epidemic of dengue/DHF in Cuba was $103 million, including $43 million for vector control plus the cost of medical services and lost salaries.

Dengue and DHF in Southeast Asia and the Western Pacific: The dengue hemorrhagic fever syndrome was recognized first by pediatricians in Manila in 1954. This severe form of the disease (DHF) has since spread through much of the Western Pacific and Southeast Asia and to the Americas and the syndrome is now among the 10 leading causes of hospitalization and death in children in at least 8 tropical Asian countries. At one time in Malaysia, a CFR as high as 7% was reported (Uma Deavi Ayyamani et al. 1986). These countries have reported at least 1.5 million hospitalizations and 33,000 deaths due to the syndrome since its first appearance in the 1950s (Halstead 1988). The disease is particularly severe in urban areas with large, dense human populations and many larval habitats with vector breeding but has been spreading to towns and villages wherever the vector is present in some density. The incidence has been particularly severe in 4 countries in Southeast Asia and the Western Pacific over the last 8 years (Table 1).

The figures in Table 1 do not include cases of uncomplicated dengue that are not reportable in any of the countries; these total many millions and cause a serious economic burden to the endemic countries in lost workdays and productivity. Dengue/DHF also appears in the Maldives, Sri Lanka, India, Bangladesh, China, Fiji, French Polynesia, Laos, Malaysia, New Caledonia, Niue, Philippines and Singapore. In Singapore, large epidemics of DHF occurred in 1961–64 and 1966–68; although an *Aedes* control program started in 1969 reduced the *Aedes* house index from more than 25% to around 5%, this did not prevent a DHF epidemic in 1973 of 1,187 cases and 27 deaths. The *Aedes* index was further reduced to between 1 and 2% in 1983, but smaller epidemics occurred in 1986, 1987 and in 1989 when 616 cases and 2 deaths were reported (WHO 1990a).

Table I. Reported cases and death from dengue haemorrhagic fever in 4 countries of Southeast Asia and the Western Pacific, 1982–90.

	Burma		Indonesia		Thailand		Vietnam	
Year	Cases	Deaths	Cases	Deaths	Cases	Deaths	Cases	Deaths
1982	1,706	49	4,665	255	22,250	159	39,805	329
1983	2,856	83	13,875	491	30,022	231	143,380	1,747
1984	2,323	39	12,710	382	69,597	451	30,496	683
1985	2,666	134	13,588	460	80,076	452	45,107	399
1986	2,192	111	16,421	600	29,030	206	46,266	511
1987	7,292	222	22,765	1,039	171,630	896	354,517	1,566
1988	1,181	65	47,573	1,527	26,926	188	85,160	826
1989	899	52	10,362	464	69,204	480	18,923	178
1990*	5,200	178	13,043	458	102,312	360	—	—

* Data up to November 1990 (Source: WHO Regional Offices for Southeast Asia and the Western Pacific).

As was expected, Thailand, with a 3-year cycle of DHF, had a serious epidemic in 1990 with 102,312 cases and 360 deaths up to November, while Vietnam expects another major outbreak in 1991.

Dengue and DHF in the Americas: The appearance of dengue, and later DHF, in Latin America followed reinfestation by *Ae. aegypti* of most of the countries from which it had been eradicated during the hemisphere-wide eradication campaign. This campaign, initiated by a resolution from the First Conference of the Pan American Health Organization in 1947, sought to control urban yellow fever through the eradication of *Aedes aegypti.* The program at first made notable progress and succeeded in eradicating the species from 9 countries, but some countries, notably Venezuela and the United States, did not join the eradication effort and many countries successful in eradicating the species were reinfested. By now, all countries in the Americas that were freed from *Ae. aegypti* have been reinfested with the exception of Uruguay, Chile, Costa Rica, The Cayman Islands and Bermuda. The infestation in Cuba has almost been eliminated.

Epidemics of dengue are occurring with increasing frequency in many *Ae. aegypti* infested countries of the Americas. More seriously, there is a considerable increase in DHF since 1980 (Pinheiro 1989). Dengue hemorrhagic fever has now been reported in Puerto Rico, Jamaica, Honduras, Cuba, Suriname, Mexico, Aruba, Nicaragua, Colombia, Brazil, Saint Lucia, El Salvador and, most recently, Venezuela. From October 1989 to mid-April 1990, Venezuela reported 12,200 dengue cases of which 3,108 were DHF with 73 deaths, two-thirds of which had occurred among children less than 14 years old (WHO 1991). The risk of serious epidemics of DHF in Bolivia, Brazil, Ecuador and Paraguay is high (Pinheiro 1989). Prior to the Venezuelan epidemic, the most serious outbreak of DHF in the Americas was in Cuba in 1981 with 344,203 cases of dengue, 1,109 of which were presumably DHF, and 159 deaths (Guzman et al. 1984).

Controlling the transmission of dengue/DHF: A high priority must be given to the control of a disease that yearly causes millions of cases, tens of thousands of hospitalizations and thousands of deaths. In 1964, the first WHO Inter-Regional Seminar on dengue and dengue hemorrhagic fever in Bangkok stated: "Other than the control of the vector, *Aedes aegypti,* no adequate preventive or control measures are available to deal with epidemics of dengue or chikungunya in urban areas" (Halstead 1966). Despite considerable research carried out on the development of a vaccine against dengue and the progress that is being made, this statement remains as valid today as it did in 1964.

As vector control is the only way of interrupting or reducing transmission of the disease for the time being, the methods of attacking the larval or adult stages to ensure a rapid, sustained, high level of reduction of adult, female populations prior to or at the time of an outbreak or epidemic must be reviewed, taking into account experience under different ecological and socioeconomic conditions. Funding for control, availability of trained personnel, and urgency of implementation are also factors to consider.

ENVIRONMENTAL CONTROL OF *AEDES AEGYPTI*

As *Ae. aegypti* in all areas of the world other than Africa breeds mainly in man-made larval habitats, the ideal method of control would be reduce the numbers of larval habitats to a point where the density of emerging adult populations would be too low for transmission of disease to occur. Attempts have been made in dengue/DHF endemic areas in Southeast Asia to prevent transmission through environmental measures undertaken by the community. The most comprehensive trial was that of Boonluan et al. (1985) in Chonburi province of Thailand between 1982 and 1985. The first year of this study was devoted to education of the community, in which the participation of health officers, local chiefs, scouts, volunteers, students and school teachers was enlisted. They were given information on the life cycle of the vector, taught how to identify larval breeding, how to protect water jars from breeding and remove non-essential water containers from around the houses, and how to use temephos sand granules when necessary. All means of communication were used; the second year was devoted to source reduction and application of sand granules, and the third year to evaluation of what had been achieved in the study. Generally, families in urban areas were less cooperative than those in rural villages. Although larval breeding was reduced by 60–80%, the Breteau index remained higher than 100 throughout the year, a level at which transmission of dengue/DHF was unlikely to cease and, in fact, did not. Soon-Young Yoon (1989) reviewed other community participation projects against DHF transmission in Southeast Asia, calling attention to mistakes made in attempting to implement them and emphasizing the need for further research. He cautioned that the results of trials might be slow in coming and that the people, not the leaders, need to be convinced that their collective well-being is threatened. Uma Deavi Ayyamani et al. (1986) carried out a KAP study (knowledge, attitude and practice) in 3 areas of the Federal Territory of Malaysia, emphasizing that control measures require the cooperation and participation of the community. In their studies, the majority of the respondents knew about dengue and associated it with a mosquito. Nevertheless, 82% of the households stored water for domestic purposes because it was customary or convenient to do so, and 32.4% because the piped water supply was unreliable.

In Cuba, environmental management has met with more success (Gessa and Gonzalez 1986); following applications of larvicides, ULV and perifocal sprays to reduce *Ae. aegypti* densities in 1981, emphasis was shifted to source reduction. The environmental sanitation campaign at times employed some 1,200 trucks and 2,000 men throughout the country. Campaign inspectors were instructed to destroy useless containers that might hold water and brush-clean the insides of water storage containers. A ban was placed on using water-bearing containers in cemeteries, and on storing water in containers without lids; growing bromeliads as hedges was banned and major lakes and ponds were stocked with larvivorous fish (measures that probably had little or no effect on *Ae. aegypti* populations). A brigade of women "vector controllers" organized to supervise the activities was authorized to impose fines for sanitary violations. Responsibility for the campaign rested with 60 licensed entomologists in medical entomology laboratories located in each of Cuba's 14 provinces and on the Isle of Youth. The authors believe that this campaign provides a good example of " . . . how *aegypti* can be successfully controlled given sufficient funds, personnel, equipment, government backing and broad public support." The campaign set an admirable example, but the conditions that ensured its success are not likely to be found in most countries of Latin America, Southeast Asia and the Western Pacific. In any event, control by environmental measures will not ensure the rapid reduction of *Ae. aegypti* populations necessary when an epidemic threatens or has broken out. Furthermore, in an environmental control program it is essential to ensure both the clean-up of containers that are actual or potential breeding sources as well as the prevention of the accumulation of new containers that may support breeding. Von Windeguth et al. (1969) studied the accumulation and loss of larval habitats in a 9-block area of a residential quarter of south Florida over a 3-month period. By the end, the number of containers was approximately the same as at the start of observations, but 50% of the containers marked at the beginning had disappeared and had been replaced by unmarked and, therefore, new containers that the population in the low socioeconomic area of the trial continuously provided.

In planning environmental control, one must consider the sheer number of containers to be dealt with in some *Ae. aegypti* infested cities and the labor or community efforts required to deal with them. In 1968, when the population of Bangkok was only 2.32 million (1989 population was approximately 5.37 million), Tonn et al. (1969) estimated that there were 301,991 houses with some 1,815,000 containers suitable as breeding sites for *Ae. aegypti* and that at least 800,000 were actually positive for larvae. It was further estimated that the adult mosquito population was replenished daily by a minimum of almost 1,900,000 *Ae. aegypti*; landing rates of 25 mosquitoes per man-hour were not unusual in areas of the city not under insecticidal control. While urban development has probably reduced the number of larval habitats in the modern center of the city, the number of new breeding sites such as automobile tires and plastic containers must now be enormous.

Efficient larviciding could eliminate larval populations in water-holding containers and eventually result in a reduction in adult populations. However, lack of immediate impact on the adult population limits use of this method to inter-epidemic periods. Nevertheless, larval control by low toxicity larvicides is the most common approach to *Ae. aegypti* control in most countries. Pant and Bang (1972) carried out a large-scale field trial of temephos (Abate®) larvicide in Bangkok, Thailand, to determine the degree of *Ae. aegypti* control that could be achieved under semi-operational conditions and the reduction in adult mosquito populations that would result from control carried out under good supervision. Most of the breeding of the species in Thailand and other countries in Southeast Asia is in large, 200-liter earthenware or cement jars kept in and around houses for storing water. The authors applied 4 rounds of temephos 1% sand-granules at a target dosage of 1 ppm to all water jars and other containers breeding *Ae. aegypti* in an area of about 3,500 houses. Although adult densities were brought down to an average of 1.04 mosquitoes/man-hour throughout the 13-month period of the trial, reduction in adult populations after the first treatment was slow and even less after subsequent treatments. The trial was least successful in a zone of substandard housing where many different types of containers were present and widely dispersed. Regrettably, this type of area represents the most serious areas of *Ae. aegypti* breeding. Thus while an efficient anti-larval control program might succeed in reducing adult mosquito densities, the reduction would be slow; control operations would have to be implemented and maintained at a high level, starting well before the period of anticipated dengue/DHF transmission. Larval control programs require close supervision and much checking to locate habitats that may have been missed and not treated. Unless diligent searches are made to find and treat the highest possible percentage of breeding sites, the results are unlikely to justify the expenditures.

RAPID CONTROL OF *AEDES AEGYPTI* POPULATIONS

Rapid control of a high proportion of blood fed adult female mosquitoes potentially circulating virus would also halt the transmission of the infectious agent and stop an epidemic. The period of dengue viremia in humans is relatively short, 7 days or less (Rosen et al. 1983); effective adult vector control might interrupt transmission of dengue even if carried out for a limited period of time in an endemic urban area or in neighborhoods where most transmission is occurring. If the area covered is not large enough, control operations might have to be repeated against mosquitoes emigrating into the treated area or those that emerged while virus was still circulating in the human population. Control may have to be maintained for several weeks to ensure that there is no recrudescence of transmission. Determining the necessity for adult vector control operations will require an effective disease surveillance program capable of rapidly detecting the onset of DHF/DSS cases or significant increase in their numbers.

ADULTICIDES FOR THE RAPID CONTROL OF *AEDES AEGYPTI*

Thermal fogs: The 2 common methods of treating extensive areas with adulticidal space sprays are thermal insecticide fogging and ultra-low volume applications of insecticide concentrates. Thermal fog application equipment applies a relatively low concentration of insecticide, usually in a carrier such as diesel oil or kerosene. By the mid-1960s, such foggings had become an integral part of the control program of most mosquito abatement districts in the United States and are still in some use. Trials were carried out against *Ae. aegypti* by Jakob (1966) using several different organophosphorous concentrates. The results showed that thermal fogs of malathion, fenthion and Dursban (chlorpyrifos) gave effective kills of *Ae. aegypti* in bioassay cages. In field trials in Southeast Asia, thermal fogs of malathion and other insecticides were found to be effective against *Ae. aegypti* though control of the wild adult populations usually only persisted for a short time, i.e., 2 or 3 days, (Lofgren et al. 1967, Gould et al. 1970, Bang et al. 1972). While often effective, thermal fogs have disadvantages as their use involves the cost of purchase and transport and use of a carrier such as diesel oil or kerosene. There is more environmental contamination than with ULV, and in cities the use of thermal fog may constitute a traffic hazard (Taylor and Schoof 1971). Thus, soon after development of the ultra-low volume method of insecticide dispersal, trials against *Ae. aegypti* were given high priority to determine its utility for their control.

Ultra-low volume applications of insecticide concentrates: From 1968, the WHO *Aedes* Research Unit (ARU) in Bangkok, Thailand, conducted a series of field trials of ULV insecticide applications to determine their efficacy for rapid emergency control of *Ae. aegypti* in urban areas. In the first trial (Kilpatrick et al. 1970), a Cessna-180 single-engined aircraft was fitted with ULV application equipment and applied 95% malathion concentrate at a rate of 219 ml/ha over 3 villages near Bangkok. The dosage did not produce an even distribution or swath width nor satisfactory mortality of caged mosquitoes or natural populations. The rate of application was increased to 438 ml/ha for a second application series. The increased dosage rates compensated for the narrow width of the swath, providing satisfactory mortalities of caged mosquitoes and a drastic reduction of natural populations. Penetration within the dwellings was good as indicated by malathion droplets on dye cards in houses and kill of caged mosquitoes indoors. In the treated area, oviposition and biting counts were greatly reduced, the latter to the satisfaction of the local human population; and it was concluded that while further development was needed, the trials showed that 90% reductions in vector populations could be achieved, which would slow the spread of a DHF epidemic.

To further study the potential of aerial ULV applications, two applications of ULV malathion were made in Nakhon Sawan, 341 km north of Bangkok, with a population of about 50,000, (Lofgren et al. 1970). The area of the city was about 7.75 km^2. To ensure complete coverage, an area of 18 km^2 was treated including almost 9,000 houses. Housing ranged from 2-story cement shophouses and low-income wooden, single family houses built on stilts, to an area of middle to high income whose buildings were also wooden but most of which were not on stilts. Ultra-low volume applications of 95% malathion were made 4 days apart and applied at a rate of 438 ml/ha by a C-47 aircraft equipped with a fuselage-mounted spraying boom. *Aedes aegypti* densities were high with pretreatment landing counts of 8.6 adults/man-hour and premise indices between 58 and 94%. The landing rate of *Ae. aegypti* was greatly reduced after each application (95 and 99%, respectively); reductions remained at 88–99% for the 10 day post-application observation period. All ovitraps within the treated area were negative for 4 days after the first application. Only 8% of the female mosquitoes dissected post-treatment were parous compared with 30% pre-treatment and 40% in the check area. Night landing rates of other species of mosquitoes were reduced by 82–97%. The authors believed that the high level of control of *Ae. aegypti* populations indicated that the method could be used for vector control during outbreaks of DHF. They recommended further study on the number of treatments and rates of application to reduce the cost. Though more expensive than ground treatment, the rapidity and ease of covering large areas by air was thought to be more important than the cost.

While the aerial applications are satisfactory, lack of suitable aircraft, appropriate spray systems and skilled pilots limit the application of the technique in many areas of Southeast Asia. Attention was therefore turned to evaluating efficacy of ground applications of ULV insecticide concentrates for control of *Ae. aegypti* populations.

The first ground ULV trials were carried out by Pant et al. (1971) in 2 small suburbs of Bangkok, each of about 2 ha with good road systems, and in the large suburb of Huay Kwang of 29 ha in the northeastern part of Bangkok with about 1,700 houses and 15,000 residents. The houses in Huay Kwang were mainly 2 stories, of wood construction, each consisting of 2–4 subunits. They had many windows, and their main entrances faced roads with houses on both sides; most houses were approachable by road. A non-treated area nearby was used for comparison. Finally, the town of Sri Racha about 100 km southeast of Bangkok with some 1,700 houses and a population of 16,000 was also treated. The town had an area of 142 ha and a densely populated center of markets and shops, surrounded by areas of low and high-income housing. Roads ran in all directions, and most of the houses faced a road. A small suburb of 200 houses 1.5 km east of the city with housing similar to that of Sri Racha was selected as control.

The 96% malathion concentrates were applied in the early morning hours by a LECO ULV cold aerosol generator mounted on a small vehicle; the rate of application was 438 ml/ha with the vehicle traveling at about 5 km/h. Evaluation was by landing rates, ovitraps, bioassays, checks on droplet densities and sizes, and in Sri Racha, by housefly counts.

Results were similar in all areas treated; two treatments carried out 3 days apart reduced adult populations by 99% and took about 2 wk to regain pre-treatment level. There was little effect on larvae in outdoor containers but a significant reduction in number of indoor containers positive. More important, there was a 90% reduction in female *Ae. aegypti* landing rates 3 days post-treatment in Sri Racha, and the percentage of parous mosquitoes was 0%. The percentage of positive ovitraps was reduced from 84.2% pre-treatment to 0% for 5 post-treatment days and was still extremely low at 12 days. Housefly counts were reduced by 47 to 100% one day after the treatment in Sri Racha. The authors concluded that the method was effective, practical and inexpensive, and could be rapidly applied at short notice even in remote places in the country. If necessary, treatment could be supplemented by use of hand-carried

ULV generators or thermal foggers for houses facing back alleys where access by vehicles might be difficult.

Despite the success of the treatments, the ARU was aware that recovery of adult populations after 2 wk would require retreatment if dengue transmission was still occurring. In preliminary field trials, indoor applications of fenitrothion by a small portable ULV applicator at dosage rates of only 5–14 ml AI/house, 2 wk apart, greatly reduced adult *Ae. aegypti* populations, which remained at a low level for 2 months; a limited residual and larvicidal activity within the houses probably reduced the recovery potential of the mosquito population (Pant and Mathis 1973). As the capacity to treat large numbers of houses by hand-carried equipment was limited, a trial of sequential applications of ULV ground aerosols of fenitrothion by vehicle mounted equipment was carried out (Pant et al. 1973) in a 14-ha area of a Bangkok suburb of 1,300 houses and population of about 10,000. Five applications of fenitrothion were made at 511–1,095 ml/ha at intervals of 11–49 days. This resulted in sustained, high level of control of *Ae. aegypti* populations for 4–5 months. The authors concluded that a LECO aerosol generator mounted on a vehicle, e.g., a jeep, could treat 3,000–4,000 houses a day and that 4 sequential applications of fenitrothion of from 580 to 730 ml/ha AI at intervals of 10–15 days could produce high level suppression of *Ae. aegypti* populations for 4–5 months. If control was started in April or May, it could suppress the population throughout the entire rainy season when most cases of DHF occur in Thailand.

In isolated small villages or towns, field trials were carried out with Fontan backpack portable mist blowers (Wirat and Pant 1973). Six treatments of 856–1,363 ml/ha of fenitrothion 83% ULV concentrate at intervals of 13–69 days provided a high level of control for 7–8 months. Pre-treatment landing rates were almost 25/man-hour. Immediately after treatment, landing and oviposition rates were zero. Ten weeks after the first and second treatments, which were 13 days apart, the landing rate was only 5.1/man-hour, a 78% reduction. Ultra-low volume applications were made by spraymen walking along paths among houses and pointing the nozzle toward the houses as they moved, enabling rapid treatment to be made of entire villages. The equipment and insecticide concentrate are readily transportable by vehicle or air to remote areas and can quickly respond to the need for controlling vectors during an epidemic of dengue/DHF.

When indoor-applications were made of fenitrothion ULV concentrates by portable mist blowers, adult mosquitoes were killed immediately, and there was some residual effect and larvicidal action. To study the effect of applying ULV fenitrothion concentrates directly into rooms and houses (Pant et al. 1974a), applications were made in a 20-ha residential area on the outskirts of Bangkok with 1,500 homes and about 11,500 population. The dosage rate was targeted at 0.1 ml/m^3 of room space and each room was treated for a count of about 20 sec. Two treatments were made 2 wk apart. There was an immediate reduction from pre-treatment landing rates of 25.2 adults/man-hour to well below 0.1/man-hour, or more than 99%. The few females collected were nulliparous. With the exception of one fully gravid female collected indoors 121 days after treatment, no further adults were captured until the 6th month. Only 8 months after treatment did adult populations show signs of recovery though landing rates remained at 0.9/man-hour. From 9 to 17 months after treatment, landing rates in the treated area were 69–92% lower than the untreated area. No oviposition was found for 8 months after treatment and remained at a much lower level than the control for some time thereafter. Although the hand-carried equipment used, the "Mity Moe Sr.," was not ideal, the principle of achieving very long term control through indoor ULV applications of fenitrothion was shown to be effective in producing an immediate and sustained reduction in adult *Ae. aegypti.*

Other ULV trials carried out in Indonesia by Seregeg and Suzuki (1987) compared single ground applications of propoxur and chlorphoxim ULV concentrates at about 600–677 ml of formulation per ha (about 70 g AI/ha for propoxur and 600 g AI/ha for chlorphoxim) against *Ae. aegypti.* In the propoxur treated area, female landing rates dropped to zero on day 4, returning to the pre-control level on day 7; in the chlorphoxim treated area, adult density declined to zero up to day 10 and thereafter increased gradually. Lam and Tham (1988) compared LECO ground applications of malathion and fenitrothion ULV concentrates against *Ae. aegypti* in Ipho, Malaysia. The trial was evaluated by bioassay only; fenitrothion had good larvicidal and adulticidal effect indoors and outdoors, but malathion had little larvicidal activity.

Because of increasing concern with the spread of dengue and the possible spread of jungle yellow fever to settlements infested by *Ae. aegypti,* the Pan American Health Organization also carried out trials of ULV applications of fenitrothion in several villages in Colombia within 45 km of Cartagena (Motta-Sanchez et al. 1978). The villages had a variety of housing types but were mainly of low income housing with mud, wood or cane walls and straw or metal roofs. Villages did not have potable water supplies, and water was stored in containers such as barrels and shallow cisterns. Small earthenware jars with water for domestic use were usually found within houses. The percentage of houses positive for *Ae. aegypti* breeding was high, ranging from 62.6 to 75.6% with an average of 68.5%. The capture rates of adult *Ae. aegypti* were also high ranging from 7.4 to 14.8/man-hour.

Several application methods were used including one village treated by LECO only for 10 cycles, 10 days apart, one treated by a LECO and motorized knapsack sprayers also for 10 cycles, and another for 10 cycles by motorized knapsack sprayers. Other villages were treated by perifocal or residual sprays with and without larviciding by temephos. Dosage rates were not calculated by quantity per ha but per house and averaged 26.5 cc per house for the treated village in which only the LECO was used and 42.6 cc per house in the village in which the LECO and knapsack motorized sprayers were both used. The 10-day cycle used was based on experience in Asia. The Colombia trials were carried out to determine the efficacy of ULV applications alone or in combination with other methods for emergency control or as a possible tool for use in *Ae. aegypti* eradication.

The ULV applications of fenitrothion, as measured by mosquitoes taken per man-hour, oviposition traps and reduction of positive containers, were very successful. Elimination of *Ae. aegypti* was achieved in the village treated by ULV applications by both LECO and knapsack sprayers, and reinfestations were not evident for 5 post-treatment inspection cycles 10 days apart, which extended 2 months into the rainy season. Where only the LECO application was made, reductions were gradual and complete elimination was not achieved, but the dosage used was considered to have been too low. Other methods such as perifocal spraying with and without larviciding took considerable time both to apply and to effect control, and the authors recommended ULV applications for use in outbreaks of *Ae. aegypti*-borne diseases.

A ULV insecticide application trial in Buga, Colombia, 78 km north of Cali, was made in 1979 by a single-engined spray aircraft applying 96% malathion concentrate (Uribe et al. 1984). The area of the city is about 3,120 ha with a population of 100,000 in some 15,000 houses. Houses have no gardens in front, and their facades are placed together forming a straight line on the street with no spaces in between. Front doors and windows are generally kept closed but the back doors and windows are open during the day. Dosages applied in the 4 flights made, two on the first day and two 6 days later, ranged from about 290 ml/ha to 682 ml/ha. All 4 flights were between 0618 and 0748 h. Both treatments killed all caged female *Ae. aegypti* left in exposed positions outdoors and indoors. The first treatment of some 290 ml/ha only slightly reduced the wild population of adult females, though the male density sharply declined. The second treatment, 682 ml/ha, produced 67 and 82% immediate reduction in resting and bait captured *Ae. aegypti* females, respectively, and complete disappearance of males with recovery to pre-spray level after 11 days. The aerial applications were quicker and easier than ground applications but more expensive.

In Africa, efficacy of malathion thermal fogs and cold mist (ULV) concentrates were compared by Bang et al. (1980) near Enugu, Nigeria, in 1977 and 1978. The objective was to identify measures for temporary suppression of natural populations of the primary yellow fever vectors in the area, *Ae. aegypti*, *Ae. africanus* (Theobald) and *Ae. luteocephalus* (Newstead). Application of both thermal fogs and ULV concentrates of malathion was by hand-carried equipment. The 5% malathion thermal fogs dispersed efficiently through the vegetation and gave more than a 90% reduction of crepuscular biting rates of *Ae. africanus*. However, there was no residual effect and the population returned to pretreatment levels within 5 days. In contrast, two successive applications of malathion (50%) as "cold mists" resulted in an immediate decline of over 95% in the adult mosquitoes, followed by a 100% reduction in oviposition for 2 wk. Population recovery was slower after treatment of a large area than when only a small community was treated, due to infiltration of mosquitoes from nearby untreated forests. The cold mists penetrated 40 m into the forest from the footpaths from which the spraying was carried out. In view of the simplicity of the operations and equipment, the authors believed that this technique could be used by locally recruited personnel for interrupting yellow fever transmission.

Other trials against *Stegomyia* vectors in rural areas of Ethiopia (Brooks et al. 1970) and Tanzania (Parker et al. 1977) showed that even a single ULV insecticide application by aircraft could reduce *Stegomyia* densities to levels at which disease transmission was unlikely.

Perhaps the first report of ULV applications used to control *Ae. aegypti* during a yellow fever epidemic was by Ribeiro (1973a) in Luanda, Angola, in 1971. *Aedes aegypti* had not been found in the city for some decades before the epidemic (Ribeiro 1973b), but investigations showed it represented 15.3% of the mosquitoes caught along the suburban belt of the city, with indoor adult densities of 5.2 females/man-hour of catch. The main larval habitat was indoor water storage containers, and the mosquito was apparently brought back into the city in used tires. Three successive cycles of aerial applications were made at rates of 500 ml/ha; post-treatment reductions were 84, 83.5 and 96%, respectively, from pre-treatment densities; population densities were reduced by 77–98% for 21 days. After the last treatment, all females were nulliparous for 11 days.

The results of ULV applications in the southern USA and the Caribbean have been less consistent than those in Southeast Asia, the Western Pacific and Africa. As part of an effort to develop new tools for use in the then *Aedes aegypti* eradication program in the USA, Eliason et al. (1970) treated 4 residential areas of 518 ha each in the southern USA with aerial applications of temephos and malathion in various combinations and frequencies. Oviposition was reduced in all areas, and where 35.5 ml/ha of malathion were applied twice a week, oviposition by *Ae. aegypti* was totally interrupted for 10 wk during the 11-wk treatment period. In view of the successful trials against *Ae. aegypti* outside of the USA, Focks et al. (1987) carried out a trial of the sequential application of malathion ULV in New Orleans, LA. In the introduction to the results of their study, they observed that trials outside of the USA have used 2- to 22-fold more insecticide than permitted in the USA; their own trial applied the US label rate of 48 ml of malathion AI/ha by LECO truck-mounted sprayers. Replicates of 11 sequential aerosol treatments applied 12 h apart during a 5.5-day period reduced mean adult captures and oviposition rates during the treatment period 73 and 75%, respectively. It was felt that oviposition was not completely reduced as adult females remained sequestered during the treatment period or were more tolerant of the pesticide, and that adult populations were not totally suppressed because of continued emergence. Adult densities recovered to pretreatment levels within 1 wk. They concluded that multiple aerosol treatments would have to be made at the current US label rate to limit spread of dengue virus if it were introduced. They also stated that aerial application would be the preferred method in case of an incipient outbreak as it would produce more uniform distribution of the insecticide, could be applied more rapidly and could use a 5.5 times higher dosage than permitted for ground applications.

A dengue outbreak occurred in Kingston, Jamaica, in 1977. Moody et al. (1979) reported on vector control measures undertaken by ground and air ULV applications of malathion, which they considered to have been effective adulticide measures and also effective in abating the epidemic.

Trials in Puerto Rico were described by the Centers for Disease Control (CDC) in 1987 (CDC 1987a). The summary of these studies states: "... there has been increasing skepticism about the efficacy of vehicle-dispensed ULV for controlling *Aedes*-borne diseases ...," and further, "There are few well-documented instances where ULV has had any real impact on transmission." No source of the reported skepticism is provided, and such a viewpoint does not seem to be supported by the success of the ULV trials that have been reported above from Southeast Asia and South America. The 13 CDC trials applied malathion or resmethrin ULV concentrates at 124 ml/min from a vehicle moving at 10 miles (16 km)/h in the early morning or late afternoon. The results failed to show adequate control of *Ae. aegypti* as measured by oviposition traps, mortality of caged mosquitoes or reduction of dengue transmission. Local *Ae. aegypti* populations have increased tolerance to malathion and resmethrin; it was not felt that this accounted for the lack of control but that the insecticide had been underdosed and was not reaching the wild adult females. As noted, successful applications in Colombia and Southeast Asia used much higher rates than the US label, which specifies 50 ml/ha, the dosage used in Puerto Rico.

Because of poor results with malathion aerial applications, a study was carried out on aerial applications of Dibrom or naled 85% against *Ae. aegypti* in San Juan, Puerto Rico, by the CDC (CDC 1987b). Applications were made by a C-130 aircraft starting at 0600 h using 5,231 liters of insecticide to treat 71,634 ha, one area being sprayed twice 8 days apart, a second 3 times on 3 consecutive days. There was considerable variability in results as measured by oviposition traps, some areas showing substantial decrease and others no change. It was concluded: "Our results have demonstrated that repeated aerial application of insecticide can have a substantial impact on the natural adult female population." The positive results indicated that the method, under optimal conditions, might suppress urban *Ae. aegypti* when dengue outbreaks seemed imminent, but further trials were necessary to refine the method and it was not a panacea due to its cost.

Chadee (1985) carried out 4 applications of 95% malathion ULV concentrate using a vehicle-mounted LECO in St. Joseph, Trinidad, in 1984. The insecticide manufacturer's recommended application rate of 130 ml/min was dispersed at 1700 h; the quantity of active ingredient per area treated was not given. Landing and oviposition rates showed that the treatments were not effective in reducing adult population densities. Mean mortality of caged adults did not exceed 42% and was significantly higher in cages outdoors than indoors. The author concluded that ground ULV spray may not have penetrated into houses separated from the streets by concrete block fences and that the ULV applications may be unsuitable for conditions in Trinidad and, possibly, Puerto Rico. As aerial spraying was effective against *Ae. aegypti* indoors and outdoors in Columbia and ineffective in Puerto Rico and Trinidad, control programs should adopt strategies suitable to local conditions.

Poor results were obtained by Hudson (1986) in spraying Paramaribo, Suriname, in 1982 with malathion 96% from truck-mounted LECO generators. The entire city of 70 km^2 was sprayed twice in 2 cycles, one taking 3 wk, the second four; applications were made between 1800 and 2200 h at a dosage rate of 50 ml/ha in the first cycle and 99 ml/ha in the second. There was only a brief reduction in *Ae. aegypti* populations after the sprayings and none in dengue transmission. The author recommended that aircraft be used for emergency ULV sprayings as ground treatment of such a large area was too time consuming. It was thought that rates of application may have been too low and further experimentation was necessary. The results were less satisfactory than those of Miranda (1979) in a ULV application in Paramaribo in 1978 in which 10 application cycles made by LECO in a 10-day cycle resulted in a considerable drop in the number of positive houses post-treatment. More frequent applications over a much smaller area may have accounted for the more satisfactory results.

Perich et al. (1990) compared ground and aerial applications of 91% malathion ULV at 438 ml/ha against *Ae. aegypti* in the Dominican Republic. Ground applications carried out by 2 vehicle-mounted LECO model ULV-500 generators. Evaluations were by ovitraps and indoor collections and caged mosquitoes. The authors recalled that Giglioli (1979) stated immediate, minimum 97% reduction of adult *Ae. aegypti* is necessary to control a dengue epidemic. In this study, neither ground nor aerial applications effected such a reduction. As elsewhere in the Caribbean, a possible explanation for the low efficacy of both application methods against indoor *Ae. aegypti* populations was that too few malathion droplets were impinging on indoor resting mosquitoes. As in Trinidad, houses were separated from the street by a 1 m high stone or cement block wall covering the length of each house front.

DISCUSSION

In most of the studies cited above, particularly in Asia and South America, ultra-low volume insecticide applications resulted in highly effective control of *Ae. aegypti* populations. In the sequential ground applications of fenitrothion ULV concentrates in Thailand, a high level of control was sustained for periods of time that would probably be adequate to interrupt dengue transmission. If applied before onset of the normal seasonal peak of dengue, these ULV applications might prevent transmission; indeed, indoor applications of 2 treatments of ULV fenitrothion eliminated natural populations of *Ae. aegypti* for 6–7 months (Pant et al. 1974a). However, in a recent review Gubler (1989), stated that ULV applications have little or no effect on wild *Ae. aegypti* populations. These opposing viewpoints, based on varying experiences, may be due to differences in the studies, including different types of housing in areas in which the trials were carried out. Different insecticides, dosage rates and droplet sizes also account for much of the difference between trials that failed to control adult populations and those that did. Virtually all trials in the Caribbean applied malathion but usually at dosages considerably lower than those that were used in Asia or South America. Some trials in the Caribbean calculated required dosage on km of road to be traveled rather than by area and consequently applied smaller dosages and in most, droplet sizes of ULV mists were not within the manufacturers' recommended 5–15 micron range, which may have resulted in poor penetration and dispersal of droplets in the air.

Gubler (1989), also observed that ULV "toxicants" applied as perifocal sprays had little or no effect on dengue transmission. However, applications carried out in several countries during epidemics of DHF were claimed to have resulted in subsequent reductions in transmission or incidence of reported cases in, among others, Semarang, Indonesia (Pant et al. 1974b), Menado, Sulawesi, Indonesia (Self et al. 1977), and Puerto Rico, CDC (1987a). Usually, reductions were judged only by reported cases and not by epidemiological investigations.

Despite lack of epidemiological evidence, reduction of *Ae. aegypti* populations was so great and sustained in many of the above studies that they would certainly fit Giglioli's postulate requiring a 97% immediate reduction in vector populations to control dengue transmission. In some trials, good reduction was not achieved because house construction prevented penetration of insecticide to indoor resting vectors or because inadequate dosages were used; better results might have been obtained with higher dosages or with other insecticides especially where resistance to malathion may have caused failure of the ULV applications to effect control. On the whole, there are enough instances where ULV applications proved successful to justify use of the method for emergency control of *Aedes* vectors and field trials in areas where it has not been tried. As the difference in efficacy between malathion and fenitrothion shows, trials should also be carried out with other insecticides and other dosage rates.

Using ULV applications for *emergency* vector control during disease outbreaks does not exclude the necessity for interepidemic environmental control with active participation of the community (Gratz 1979). Nevertheless, if *Ae. aegypti* transmitted disease occurs, environmental management has obviously been inadequate and rapid measures are needed to control transmission. Until an effective, safe and practical vaccine for dengue is available, ultra-low volume application of effective insecticides at adequate dosages appears to be the only measure available for the emergency control of *Aedes* vectors in most urban and periurban areas. The ULV applications should not be used in routine control as this may expedite development of insecticide resistance.

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