DDT: The fallen angel

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Dichlorodiphenyl trichloroethane (DDT) was at one time highly efficient in malaria control. However, it has lost its effectiveness in vector control and collateral benefits of killing nuisance insects. Malaria control in rural India is based on the indoor residual spraying of insecticides. The principal insecticide used in malaria control is DDT. It has been banned under the Stockholm Convention on Persistent Organic Pollutants under the United Nations Environment Programme (UNEP) auspices in May 2001. The position of the World Health Organization (WHO) for DDT is the mirror image of UNEP. The Stockholm Convention makes provision for the use of DDT in genuine cases. India has sought exemption for the use of DDT in vector control. This article examines the role of DDT in malaria vector control and argues that DDT-spraying produces diminishing returns and eventually becomes counterproductive. Instead, the National Anti-Malaria Programme will do well by abiding with the UNEP/WHO call, reducing reliance on DDT and changing over to the bioenvironmental methods, and investing resources in research and development in the foreseeable future.

THE Stockholm Convention on Persistent Organic Pollutants (POPs) was signed in May 2001. It bans, inter alia, the use of nine intentionally produced POP chemicals, mostly organochlorine pesticides, including dichlorodiphenyl trichloroethane (DDT)[1]. It does, however, also contain, in Annex B Part II, conditions under which governments can be exempted from the ban on use of DDT, for the exclusive purpose of vector control. The Convention establishes as its ultimate goal the complete elimination of DDT production and use, once effective and affordable alternatives have become available that will allow countries relying on DDT to ensure at least the same level of transmission interruption. Annex 1 of the report of a WHO study group on vector control for malaria and other mosquito-borne diseases[2] provides guidelines on the use of DDT in vector control. Subsequent to these developments, the action plan of WHO for the reduction of reliance on DDT in disease vector control has been published[3].

DDT, at one time considered a panacea, has lost its effectiveness in malaria control. This is partly due to six decades of spraying resulting in physiological resistance to DDT and/or pronounced exophilic vector behaviour encouraging extra-domiciliary transmission. DDT is still used in malaria control in India, although there is overwhelming evidence of its failure in malaria control. This article examines the value of DDT for future malaria control in India. Data available since the launching of the National Malaria Control Programme (NMCP) in 1953 indicate that while DDT was once extremely effective in controlling malaria, it has lost much of its effectiveness, particularly in the rural areas where most of India's malaria occurs. Even though it may reduce transmission intensity to a sizeable degree in some places, this is not sufficient to prevent epidemics. Moreover, data clearly indicate that in numerous areas subjected to routine spraying of DDT, malaria continues to either stagnate or increase. Much of the ineffectiveness of DDT is the result of resistance in the main rural malaria vector *Anopheles culicifacies*. Poor operational planning may have contributed to the development of such resistance, and it is unlikely that changes in operational practices will increase the effectiveness of DDT. In contrast, there is compelling evidence that community-based bioenvironmental methods, particularly when compared to DDT-based house-spraying programmes, are extremely effective in reducing malaria transmission. Accordingly, rather than maintaining or increasing its investment in DDT-based spray programmes, the National Anti-Malaria Programme (NAMP) would do well by increasing its investment in bioenvironmental methods, building on previously demonstrated successes.

Early history of success of DDT in India

DDT was first introduced in India in 1944 by the British and American armies in Orissa and Karnataka. Between 1948 and 1952, malaria-control demonstration projects revealed the unprecedented effectiveness of DDT in interrupting transmission even at 0.5 g/m^2 dosage[4]. In 1953, the Government of India (GOI) launched the NMCP, with indoor residual spraying (IRS) of DDT at 1 g/m^2. Simultaneously, it established a DDT production plant (Hindustan

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Insecticides Ltd., HIL) to meet the needs of the NMCP. In 1958, the GOI joined the WHO global eradication effort and the NMCP was turned into the National Malaria Eradication Programme (NMEP), with a phased malaria eradication programme, viz. (i) preparatory phase of one year for planning, procurement of supplies and training of staff, (ii) attack phase for indoor residual insecticide spraying to achieve total coverage till the transmission gets interrupted for a minimum period of three years; (iii) consolidation phase of surveillance to detect all human infections and radical treatment of all cases, and focal spraying to eradicate residual foci, and absence of any new indigenous case for three years, and (iv) maintenance phase with maintenance of malaria-free status as a perpetual activity with responsibility of vigilance and eradication of foci by the general health services[5]. Following this strategy, by 1968–69 NMEP was well underway towards achieving its national objective of malaria eradication. Indoor residual spraying of DDT had resulted in malaria eradication in a population of 296 million, covering 58% of the country's population at risk of contracting malaria[6]. At the start of the DDT-based malaria control campaign in 1953, the estimated annual incidence amounted to 75 million cases and 8,00,000 deaths. Reliable surveillance only gradually developed during the eradication period, but it is generally accepted that the incidence rate reached its lowest value in 1966: 1,08,394 reported cases and no malaria deaths at all. As a collateral benefit, DDT eliminated kala-azar and plague and wiped out nuisance household insects. Such a spectacular success made the use of DDT popular[1].

Fading impact of DDT

Slowly but steadily, rural mosquito populations (*A. culicifacies*) evolved to withstand or avoid the killing effect of DDT. That was the beginning of the decline of DDT. As resistance spread, a dramatic resurgence of malaria occurred in the second half of the 1960s and in the 1970s. Malaria in India basically had been a rural disease, and therefore NMEP was a rural malaria control programme. During the resurgence of the disease during the late 1960s onwards, malaria cases were multiplying in the urban areas, and the disease was seen diffusing from urban to rural areas that were in the maintenance phase. To address the emerging urban malaria problem, in 1970–71 NMEP implemented the Urban Malaria Scheme (UMS). A total of 131 towns with 40,000 or more population and malaria incidence in excess of two annual parasite incidences (APIs) at ten annual blood examination rates (ABERs) were identified. UMS was implemented in phases and it took two decades to cover the identified towns[7,8]. The vector of urban malaria, *Anopheles stephensi* is best addressed by larval control rather than indoor residual spraying, because spraying lacks operational feasibility. Malaria transmission is now recorded from many areas which were at one time freed from the disease, although variations in its intensity are as much a function of the efficiency of disease vectors as of the effectiveness of control programmes, especially indoor house spraying with DDT. For example, malaria in the rural areas in South India is less prevalent not because of the efficient spraying of DDT, but because of the predominance of *An. culicifacies* species B (a poor vector) rather than species A (an efficient vector), as is the case in North India[9].

Although malaria incidence had been grossly underestimated, by 1976 parasite-positive blood smears hit a high of 6.46 million cases. In 1977, malaria eradication was superseded by the Modified Plan of Operation (MPO) with a more focused attack in areas where the API was two or more. Under the MPO, which witnessed a declining trend in malaria, DDT (indoor residual spraying) was the principal insecticide. In areas with DDT resistance, HCH was sprayed and in double-resistant (DDT and HCH) areas, Malathion was used. Malaria incidence statistics indicates a drop in malaria cases from 1977 to 1990, but it is not clear how much of this was attributable to spraying of homes and how much of it was a consequence of enhanced case detection and treatment with chloroquine. Nevertheless, the impact of detection and treatment is most clearly illustrated by trends in the incidence of malaria caused by *Plasmodium vivax* and compared to cases caused by *P. falciparum*. Cases of *P. vivax* declined from 4.3 million in 1977 to 1.3 million in 1990, a decrease of 70%. In contrast, *P. falciparum* cases increased by 63%, from 4,61,484 in 1977 to 7,52,118 in 1990. This was the result of the high sensitivity of *P. vivax*, and increasing resistance of *P. falciparum* to chloroquine, first detected in Assam in 1971 (ref. 10). In 1988, the Swedish International Development Agency terminated its ten-year programme, initially focusing on *P. falciparum*-dominated areas in the northeastern states of India. Despite DDT-spraying, *P. falciparum* cases were rising and spreading in the rest of the country, including the problem of drug-resistant malaria[11,12].

Current reliance on DDT for malaria control

Today, the Central Government spends 25–30% of the health budget on malaria control. Malaria control is based on 50 : 50 cost-sharing basis between the GOI and the state governments (100% by the GOI for northeastern states). The committee of secretaries to the GOI determines the exact amount of DDT sprayed annually. The NAMP (formerly NMEP), sprayed 42,200 metric tons DDT (50% WP) including 11,600 metric tons for kala-azar disease control) during the 9th Five-Year Plan (1997–98 to 2001–02) and envisages the use of 66,000 metric tons DDT (50% WP) (including 13,000 metric tons for kala-azar) during the 10th Five-Year Plan (2002–03 to 2006–

07). This reliance on DDT for malaria control is misplaced, considering the substantial scientific evidence of its ineffectiveness. Even at the height of malaria-eradication efforts, DDT-spraying did not interrupt malaria transmission in 51 million people after 13 to 17 years of regular DDT spraying, which had started in 1958. In contrast, active malaria transmission was interrupted within three years of spraying under attack phase of the eradication programme. NMEP units (a unit was one million population) that did not respond to DDT-spraying were scattered all over the country and vectors responsible for the transmission included all major species: *An. culicifacies*, *An. stephensi*, *An. fluviatilis*, *An. minimus*, *An. dirus* and *An. sundaicus*[6]. In later years (mid-1960s onwards) malaria was seen rising in maintenance and consolidation units throughout the country, resulting in the reversion of large populations to the attack phase. Table 1 gives the NMEP data on the reversion and failing impact of DDT (quantity given in 75% WP, as imported DDT was 75% WP) in the control and containment of malaria.

If DDT had been successful in interrupting malaria, one would expect to see levels of consolidation phase criteria maintained at 0.1 case per thousand population. But scrutiny of data on DDT and malaria reveals that the failure of DDT in interrupting malaria transmission was widespread, as illustrated in Table 2 by NMEP API data for 1986–95.

Further observations supporting the failure of DDT in malaria transmission interruption include the following:

- In Gujarat, the API was rising in all districts receiving DDT spraying (1986–91).
- In Karnataka, Primary Health Centres (PHCs) recorded substantial increases in API following two rounds of DDT spraying (e.g. in Gudibanda PHC from 2.4 in 1989 to 178 in 1997; in Begepalli PHC from 1.9 in 1988 to 65.4 in 1990; in Javagal PHC from 1.8 in 1992 to 176 in 1995, and in DM Kurke PHC from 10.5 in 1991 to 97.9 in 1994).
- Major malaria epidemics were witnessed in areas where DDT was used for indoor spraying. Examples include four districts in Rajasthan, Manipur and Nagaland (1994); 3 in Maharashtra, 7 in eastern Rajasthan, and Mewat region in Haryana (1996); 17 in Assam and 3

Table 1. Achievements in malaria control under the National Malaria Eradication Programme

Year	Attack	Consolidation	Maintenance	Total	DDT (75% WP) sprayed in metric tons
1958–59	225.25 (276)			225.25 (276)	14878.0
1959–60	386.25 (335)			386.25 (335)	21544.3
1960–61	387.00 (344)			387.00 (344)	30293.1
1961–62	390.00 (424)	–	–	390.00 (424)	26307.3
1962–63	249.53 (278)	140.47 (157)	–	390.00 (435)	25003.9
1963–64	162.70 (185)	228.30 (260)	–	391.00 (445)	13741.2
1964–65	103.01 (120)	209.48 (243)	78.51 (92)	391.00 (455)	14643.1
1965–66	80.26 (93)	170.36❶ (203)	142.63 (170)	393.25 (466)	12058.7
1966–67	55.85 (66)	134.09❷ (162)	203.31 (254)	393.25 (476)	8843.2
1967–68	44.55 (51)	120.74❸ (147)	227.96 (291)	393.25 (489)	8496.5
1968–69	41.60 (50) + 51.785*(66) + 19.60**(25)	122.17 (157) – 51.785*(66)	229.48 (296) – 19.60**(25)	393.25 (502)	12222.8
Total	112.985 (141)	70.385 (91)	209.88 (270)		
1969–70	40.837 (48) + 52.223*(69) – 14.404 (19)**	120.963 (160) – 52.223*(69)	231.450 (268) – 14.404**(19)	393.25 (514)	13774.9
Total	107.464 (136)	68.740 (91)	217.046 (287)		
1970–71	39.372 (48) + 51.483*(69) + 14.404**(19)	119.708 (162) – 51.483*(69)	234.170 (317) – 14.404**(19)	393.25 (527)	11219.5
Total	105.259 (136)	68.225 (93)	219.97 (298)		
1971–72	39.112 (48) + 50.513*(68)* + 10.404**(14)	117.938 (161) – 50.513*(68)	236.200 (326) – 10.404**(14)	393.25 (535)	12492.1
	100.029 (130)	67.425 (93)	225.796 (312)		

Source: Ref. 6. Numbers in brackets indicate the population in millions.
*Reverted from consolidation to attack phase.
**Reverted from maintenance to attack phase.
❶Includes 11.59 unit areas temporarily reverted to attack phase.
❷Includes 16.66 unit areas temporarily reverted to attack phase.
❸Includes 23.95 unit areas temporarily reverted to attack phase.

districts in Gujarat (1997). Between 1999 and 2001 malaria epidemics occurred in DDT-sprayed areas in Assam, Andhra Pradesh, Bihar, Chhattisgarh, Gujarat, Madhya Pradesh, Orissa and Rajasthan. Malaria epidemics that had been completely eliminated during the height of DDT's success many decades ago are now back with increasing frequency and intensity, including areas receiving regular sprays of DDT.

- The Health Department of Maharashtra reported an increasing trend of malaria even after two rounds of DDT indoor spraying between 1995 and 1997, with a 75–83% coverage of rooms in houses. Monitoring in 74 villages revealed that malaria transmission continued, and cases had sharply increased by the third quarter of 1997. In November 1997, a special spraying round with Lambda-cyhalothrin (10% WP) managed to interrupt malaria transmission[13].

Such reports from areas undergoing regular spray-rounds with DDT are becoming increasingly common. They strongly indicate that while DDT may remain effective in malaria-vector control in other countries, e.g. South Africa and Madagascar (which, under the Stockholm Convention, are free to choose DDT in the absence of better alternatives), this is no longer the case in India.

Scientific, operational and social reasons for ineffectiveness of DDT

The declining effectiveness of DDT is a result of several factors which frequently operate in tandem. The first and the most important factor is vector resistance to DDT. All populations of the main vector, *An. culicifacies* have become resistant to DDT[6,14]. The excito-repellent effect of DDT, often reported useful in other countries, actually promotes outdoor transmission and therefore helps maintain a huge malaria burden under the influence of *An. culicifacies*, *An. dirus* and *An. sundaicus*. Unfortunately, India's warm climate, outdoor sleeping habits, night duties (tribal populations leave their houses at 2–3 a.m. to collect forest products) contribute to outdoor transmission encouraged by the exophilic or excito-repellent action of DDT.

Table 2. Malaria incidence in DDT protected areas under the influence of major malaria vectors

Vector species	District/area	API nine year average (minimum and maximum API)
An. culicifacies	Chandigarh	29.25 (11.72–55.86)
	Dadar Nagar Haveli	56.60 (40.00–115.9)
	Bhopal (MP)	9.40 (4.70–11.70)
An. culicifacies and *An. fluviatilis*	Phulbani (Orissa)	29.70 (21.70–43.50)
An. culicifacies and *An. stephensi*	Barmer (Rajasthan)	10.00 (0.20–27.60)
An. minimus and *An. fluviatilis*	Karbi Anlong (Assam)	21.10 (15.60–24.80)
	Jaintia Hills (Meghalaya)	12.60 (0.80–38.40)
An. minimus	Lunglei (Mizoram)	48.40 (24.40–82.80)
	Jalpaiguri (West Bengal)	07.70 (2.60–16.50)
An. sundaicus	Lunglei (Mizoram)	48.40 (24.40–82,80)
	Car Nicobar Islands	37.10 (17.8–60.60)

The second factor contributing to the ineffectiveness of DDT is its inappropriate use. Because India's surveillance system has broken down (there is a 40–60% vacancy rate among surveillance workers and laboratory technicians), the application of DDT is not evidence-based.

Third, DDT, cheaper by weight than alternative pesticides and manufactured indigenously by government-controlled HIL, is sprayed with the false belief that its excito-repellent action prevents transmission.

Fourth, mud-plastering of sprayed walls, a phenomenon mainly seen in tribal communities, cancels the efficacy of insecticide-spraying. These communities suffer from a high burden of malaria, predominantly caused by *P. falciparum*. Indoor residual spraying performs poorly in such areas. In addition, high refusal rates by individual households caused by the return of mosquitoes and malaria, seriously undermine the public health value of indoor residual spraying.

Fifth, coverage rates are too low. To be effective, a DDT-spraying programme must cover a high (> 90% of structures) portion of the targetted area. However, India historically has undersupplied its spraying programme. For example, a study by NMEP reported that during the period of MPO from 1977 to 1984, insecticide-spray (DDT, HCH and Malathion) could cover only 40–60% of the targetted areas. Even if coverage increased, there is no assurance that the effectiveness of DDT would be increased, because of the resistance problems described above.

It should also be noted that, as mentioned before, DDT is inappropriate for use in urban malaria situations, where building codes and anti-larval programmes can provide effective weapons. Moreover, controls over DDT distribution are weak. Consequently, DDT is diverted to illegal agricultural uses, potentially compromising the sale of export crops. Its use on crops at concentrations used for public-health purposes, carries a further risk of promoting resistance.

The Stockholm Convention and India's use of DDT

Annex B Part II of the Stockholm Convention on POPs states: 'Each party that produces and/or uses DDT shall restrict such production and/or use for disease vector control in accordance with the World Health Organization recommendations and guidelines on the use of DDT and when locally safe, effective and affordable alternatives are not available to the Party in question'. WHO recommends DDT use for malaria vector control, provided all the following conditions are met[2,15]:

(i) It is used only for indoor spraying. (ii) It is effective. (iii) The material is manufactured to the specifications issued by WHO. (iv) The necessary safety precautions are taken in its use and disposal. Clearly, in India the second and third conditions are not met and widespread resistance together with high refusal rates have rendered DDT ineffective. DDT is manufactured in India as 50% WP (not 75% according to the WHO specifications) and sprayed at a concentration of 1 g/m^2 (instead of the WHO recommended 2 g/m^2). With respect to the first and last conditions, no regulatory safeguards have been put in place in India to curb the well-known phenomenon of diversion of DDT to uses other than vector control. More than ten years after its ban in agriculture, DDT and its metabolites are found in excess of maximum permissible levels in lakes, tap water and human blood samples. Often, *An. culicifacies* breeding places contain high levels of DDT, thus encouraging the development of DDT resistance at immature stages[16]. Available data indicate that DDT use for indoor house spraying has a clearly discernible impact both on DDT levels in humans and the environment[17]. A comparative study of areas under bioenvironmental control and under conventional DDT spraying, monitored at an interval of eight years, revealed that only in sprayed areas DDT and its metabolites exceeded the maximum permissible limits in human breast milk and bovine milk. DDT residues in soil were 74 times higher and in whole blood, eight times higher. In groundwater, no DDT was detectable when alternatives were used against the presence of 0.18 to 0.07 µg/l in sprayed areas[18,19]. Obviously, either DDT sprayed on walls eventually contaminates the environment or it ends up in the environment through diversion for illegal uses.

In India, DDT was sprayed @ 1 g/m^2 since the beginning in 1953. Gradually, vectors developed resistance or a pronounced exophilic behaviour. Later trials with 2 g/m^2 DDT did not improve the impact on malaria transmission[20–22], but spraying Deltamethrin suppressed vectors and malaria in DDT and HCH-resistant populations[13,23], although resistance has already appeared to synthetic pyrethroid insecticide in *An. culicifacies*[24].

Alternatives to DDT

While affecting and controllable over large areas, malaria is a local disease whose magnitude is a function of the efficiency and feeding characteristics of local vectors, changes in local environments (water-bodies, rainfall, population movement, development projects, and other human behaviour), the funding for and operational effectiveness of malaria control programmes, etc. In India, we have a strong knowledge base on the biology and ecology of our local vector species. As a result, successful community-based malaria control has been demonstrated in several states using bioenvironmental methods[25–27]. Wherever required, insecticide-treated bed-nets replaced or supplemented these methods, while outbreaks were brought under control by selective spraying. These are low-cost, sustainable interventions that can be deployed through the primary health care system or merged with other actions at the community level. Further, impetus could be given to a shift in approach by development of an Integrated Vector Management strategy. It would operate in a decentralized environment with considerable involvement at the district and community level. In many rural settings it could be combined with Integrated Pest Management and benefit from existing mechanisms for farmer or 'Panchayat' empowerment, such as Farmer Field Schools. Such a strategy would build on all available vector-control methods, starting with bioenvironmental control and personal protection, but not necessarily excluding chemical methods such as indoor residual spraying, completely. It would, on the whole, be less reliant on insecticides and therefore allow for the introduction of modern, effective, more expensive products and formulations that could be used more sparingly. It would treat the limited number of effective insecticides at our disposal as precious resources, to be used only in cases where control by non-chemical methods leaves malaria transmission at unacceptably high levels. Most importantly, it will finally allow putting an end to the DDT chapter in Indian malaria vector control.

Conclusion

Summing up, three main factors have contributed to the ineffectiveness of DDT in India. First, the widespread phenomenon of resistance underscores why those launching the eradication programme more than four decades ago sensed they had only a few years to eradicate malaria before resistance set in. While in places like Madagascar and South Africa resistance is not a problem; there is overwhelming evidence that it is a problem in India.

Second, NAMP has been unable to meet the minimum requirements for programme efficacy set out by WHO – the formulation (75% WP) and dosage of DDT (2 g/m^2) to be applied in vector control. Indeed, evidence indicates that these factors have profoundly affected the useful life of DDT.

Third, such social and cultural factors as widespread resistance to the spraying of homes reduced the coverage necessary to accomplish the goals of eradication and control.

As NAMP formulates its future plans for malaria control, it should determine if any of these factors is likely to improve. The clear answer is no. Resistance will not go away and arguably will get even worse. There is no reason to believe that operations in the future will be better than what they were in the past, and that social resistance to spraying will decrease. In view of these considerations, and of the successful demonstrations of alternative approaches to sustainable malaria control, the path for

India's future malaria control programme clearly lies away from DDT.

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