9 | SUPPRESSING THE VECTOR

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9.1 | Introduction

Vector control is the main attack weapon for reducing malaria transmission.[1] It is a lead intervention in the Roll Back Malaria (RBM) Global Malaria Action Plan. It is the only tool that is capable of bringing intense or moderate transmission down to the low levels where elimination is within reach. It can also play an important role in knocking out the last foci of transmission in the later stages of elimination. In this chapter, we provide an overview of available vector control tools and a summary of the essential characteristics of the various methods. We then consider how these methods fit within an elimination context and their respective roles at each stage of the process. Finally, we consider a few examples of operational issues in implementation and some critical constraints to the effectiveness of vector control.

9.2 | Introduction to the *Anopheles* Vector Species

Malaria is transmitted by female mosquitoes of the genus *Anopheles*. About 70 species of *Anopheles* transmit human malaria, but only about 30 of these are of major importance as vectors. In any given area, just a few *Anopheles* species will be responsible for most malaria transmission. Individual species

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BOX 9.1 | Main Messages

- Vector control is a vital attack weapon of elimination. It is the only intervention capable of reducing transmission in the early stages of elimination.
- In the later stages of elimination, the role of vector control is to knock out the remaining foci of transmission; post-elimination, its role is reducing outbreak risk and as a defense against reinvasion.
- The deployment of vector control must be carefully adapted both to the biology of the local species of vector mosquitoes and to the local epidemiology of malaria.
- Although some countries have kept up intensive and successful vector control operations for several decades, many others have encountered serious technical and operational obstacles to sustainability, including insecticide resistance in the mosquitoes and gradual declines in both the technical quality of spraying operations and acceptance by target communities.
- If transmission is suppressed by vector control for a long period and this suppression is then withdrawn suddenly, rapid resurgence of malaria can sometimes lead to catastrophic epidemics with substantial loss of life.
- Without a substantial expansion in training, the scarcity of specialized expertise in vector control will be a growing practical constraint on the delivery and effectiveness of vector control programs.

vary widely in their breeding and biting behavior. The main characteristics that determine whether an *Anopheles* mosquito is a major vector of malaria are its blood feeding preferences (predominantly animal or human) and longevity. The range and type of breeding place can be highly variable for different mosquito species.

Anopheles mosquitoes occur throughout the world, with the exception of the Polynesian and Micronesian islands of the Pacific Ocean and most arctic regions. Following is a list of some examples of biological and behavioral differences.

IN AFRICA

The principal vectors in sub-Saharan Africa belong to the *A. gambiae* or *A. funestus* groups of species. The vector species within these groups feed and rest indoors at night (i.e., are endophagic and endophilic), so insecticide-treated nets (ITNs) and indoor residual spraying (IRS) are effective against them.

The relative efficiency of these African species as vectors, compared with their equivalents in other continents, is one of the main reasons that 90% of the world's malaria mortality occurs in Africa.

These species do not breed well in man-made containers or in water with organic pollution, so they tend to be excluded by the process of urbanization; for this reason, the intensity of transmission in Africa tends to be much lower in urban areas.

IN INDIA

Conversely, India is the only part of the world where malaria transmission is often more intense in town than in the surrounding countryside. This is because one of the main Indian vectors, *A. stephensi*, is the only important malaria vector that has adapted to breeding in man-made containers, such as rooftop water tanks. Transmission in the rural areas is sustained by members of the *A. culicifacies* complex, another very effective vector.

IN SOUTHEAST ASIA

The most efficient vectors in Southeast Asia, *A. dirus* and *A. minimus*, are strongly associated with forests. Hence, malaria transmission tends to be most intense in forested areas, many of which are in remote mountainous regions, often on the borders between countries.

The African and Indian vectors tend to bite and rest indoors and so are well controlled by indoor spraying. By contrast, the forest vectors of Southeast Asia, and the equivalent species in the Amazon basin, such as *A. darlingi*, are all much less likely to rest indoors and so are less well controlled by spraying.

9.3 The Vector Control Menu

IRS—INDOOR RESIDUAL SPRAYING

In terms of its immediate impact, IRS remains the most powerful vector control technology to reduce and interrupt malaria transmission.[2] This reflects two critical aspects of the biology of the vector. The first concerns the biting habits of anopheline mosquitoes. Tropical *Anopheles* mosquitoes feed repeatedly, every 2 or 3 days, and most of the important vector species tend to bite humans indoors and then rest on the walls of the bedrooms. This means that they risk being killed every time they feed indoors. The other key biological fact is that it takes malaria parasites approximately 11 to 14 days to mature inside the mosquito before they are ready to be passed on to the next human host, and in the tropics, only a small minority of *Anopheles* females live that long. The critical advantage of IRS is that it not only reduces the abundance of mosquitoes but, more importantly, reduces their lifespan. This makes a big difference; even a marginal reduction in longevity will produce a dramatic reduction in transmission.[3]

The advent of house spraying in the 1950s made effective malaria prevention feasible for the first time in scattered rural populations. The impressive initial achievements of large-scale IRS led to the creation of the first global malaria eradication campaign, and the eventual failure of this campaign was also attributable in part to vector control problems that were anticipated but underestimated. First, a long series of pilot IRS trials failed to demonstrate that the highly intense transmission in tropical Africa could be interrupted, even by careful deployment of a combination of the most powerful malaria control weapons.[4, 5] Meanwhile, in much of Asia, progress had slowed down or stalled because of problems related to logistics, reduced compliance from target populations, insecticide resistance, and vector behavior.[6] Eventually, the world reluctantly concluded that global eradication was "technically unfeasible."

The same caveats that applied to the first eradication campaign can be applied to elimination campaigns today. IRS is a logistically demanding intervention: it is easy to do badly and is then ineffective. Proper infrastructure that can sustain coverage in a targeted area must be in place, including a system for selecting the right insecticide, adequate supervision of the program, enforced safety measures for sprayers, reliable and up-to-date spray equipment, frequent monitoring of progress, and careful evaluations of the program. The local epidemiological, entomological, and transmission patterns of the targeted areas must be understood and carefully monitored throughout the program. Furthermore, as IRS must be deployed on the insides of homes, community acceptance of IRS must be obtained to ensure that targeted populations understand and will consent to the spray program.

For elimination, IRS may have to be intense, thorough, and prolonged; the problem is that this may also intensify selection for resistance. The speed at which resistance is selected is unpredictable. The crucial point is that there are only four classes of insecticide recommended for IRS, so running out of effective compounds is possible. This means that there may be a limit to the period over which very intensive IRS can be sustained.

Insecticide choice may be further constrained by available formulations. Current IRS insecticide formulations last from 2 to 6 months, and this is a major constraint on its effectiveness. Formulations have improved recently, but with the exception of DDT, which is intrinsically stable, most IRS formulations last less than 4 months, so there is room for considerable further improvement.

BOX 9.2 | Is a Combination of Both ITNs and IRS More Effective than Either Alone?

So far, there is insufficient operational data to answer this question, which is important for the purposes of elimination at the geographical margins of malaria. From the point of view of disease control, however, we must not forget that the majority of children in Africa (who suffer about 85% of the global burden of disease) so far have no access to either of these interventions. For the moment, therefore, the public health priority at the regional level must be to extend coverage with either IRS or ITNs, whichever is more convenient locally.

ITNs—INSECTICIDE-TREATED NETS

Insecticide-treated nets have become the most widely used form of vector control, not because they are more powerful than IRS, but because they are usually less demanding logistically and coverage is easier to sustain. Ordinary ITNs need to be retreated every year or so, but this is not so with long-lasting insecticide nets (LLINs), which are designed so that the insecticide lasts as long as the net. ITNs work in two ways: first, they protect the individual user against biting, and second, they can kill some of the mosquitoes that try to bite. Like IRS, use of ITNs can produce a community-wide reduction in transmission.[7] Untreated nets give valuable protection against malaria, and their public health utility should not be underestimated, but the addition of the insecticide approximately doubles this protection.

ITNs (including LLINs) can be distributed in large-scale campaigns or through routine health contacts such as antenatal care and childhood immunization services. When the aim is disease control in high-transmission settings, they may be targeted to young children and pregnant women. In an elimination program, they should be provided to every sleeping place, as a means of general transmission control.

Community acceptance of ITNs, as with IRS, is essential if the targeted population is to use the nets properly. For example, some communities have a long tradition of net use, with well-established preferences for shape, size, color, and fabric. In places with a lot of nighttime nuisance biting by mosquitoes, most people who are not otherwise protected are happy to use a net, but it is often important to emphasize the need to use ITNs even when levels of nuisance biting are low. Engaging the community in the decision-making process is important, as are information, education, and communication (IEC) campaigns.

ATTACKS ON BREEDING SITES—SOURCE REDUCTION, ENVIRONMENTAL CONTROL, AND LARVICIDING

Before the advent of DDT, destroying the larvae of mosquitoes was the only available form of vector control.[8] However, if the aim is to interrupt disease transmission, attacking the larvae tends to be less effective and efficient than attacking the adults. Larval control is not effective unless it is extremely thorough, and this is difficult to achieve. Most malaria vector *Anopheles* species prefer breeding sites that are small, numerous, scattered, and shifting. The critical obstacle is not how to kill the larvae in the known breeding sites but how to find and routinely treat all the sites. Each species has its own idiosyncratic preferences, so detailed knowledge of the specific kinds of water exploited by the local vectors is needed: some vectors breed in freshly formed puddles, others in rice fields or in established pools or marshland. The larval control has to be deployed and constantly sustained over a large area; tropical malaria vectors take only a week to complete their larval development and can easily fly 4 or 5 kilometers. For all these reasons, effective larval control requires highly specialized expertise, substantial investment, and constant effort.

There are opportunities for effective larval control when breeding sites are few, fixed, and easy to identify. Most of the famous examples of successful larval control have occurred in circumstances where, for one reason or another, breeding sites were clearly identifiable and confined to locations that were well defined and fixed.[9] Such situations are not common, but experience shows that when they occur, there are sometimes opportunities to knock out all the sites with just one economical intervention. The key rule is "don't make things worse." In many places, a substantial proportion of the local breeding sites are man-made, typically as an inadvertent side effect of some otherwise beneficial activity. Often these problems are a consequence of ignorance and misinformation about mosquitoes and how they breed.

9.4 Comparing the Impact of Alternative Vector Control Methods on Transmission

Eliminating the vector is not possible; our current methods of vector control are not normally capable of reducing vector numbers to zero over a large area. As we have seen, some methods of vector control (such as attacks on breed-

> **BOX 9.3 | Genetic Control**
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> At present, the use of genetically modified mosquitoes is an area of intense research. Such methods might eventually be useful for elimination purposes, but there is no genetic control technology that is likely to be practical for application against malaria vectors in the next few years.

ing sites) act simply by reducing mosquito numbers and reduce transmission in simple direct proportion to their effect on vector population size. Other methods (such as IRS) have a larger impact on transmission by reducing not only the size of the vector population but also its capacity to transmit malaria.

The intensity of malaria transmission varies across a remarkably large range. For example, in areas with moderately intense transmission, people are typically exposed to an average of 10 to 100 bites from infectious mosquitoes per person per year. At the other end of the scale are locations that have reached the threshold between the pre-elimination and the elimination phases of the process, a point that is defined by the World Health Organization in terms of an observed incidence of 0.1 cases per 1,000 persons per year. A difference of about 100,000-fold separates these two situations. Converting any given location from the former condition into the latter is beyond the capacity of control methods that reduce mosquito population size but have no other effect on vectorial capacity. In the future, this might become feasible if researchers succeed in developing methods, almost certainly involving genetic modification of the mosquitoes, that can eliminate the ability of local vector populations to transmit malaria altogether. At present, this essential first giant step in the elimination process can only be done with methods such as IRS and ITNs, which work by reducing vector longevity as well as vector population size.

9.5 | How the Role of Vector Control Evolves Through Phases of Elimination

Because of the characteristics reviewed above, the relative roles of these different forms of vector control evolve—before, during, and after elimination is achieved. These changes are summarized in Table 9.1. Various terms have been suggested for the successive stages of the elimination process (Chapter 3); here we use our own functional classification, which focuses on the role of different vector control methods during each phase.

PREPARATORY PHASE

Planning is the key to effective vector control.[10, 11] Accurate information is needed on the biology and behavior of the vector mosquito species and on the geography and epidemiology of the malaria foci to be attacked. This informa-

TABLE 9.1 | Allocation of malaria suppression measures to different phases of an elimination program

	Attack phase	Elimination stages	Consolidation	Maintenance
Rationale and role	• General reduction in transmission • Maximum intensity and complete coverage throughout, with aim to interrupt transmission completely	• Intensive attacks on remaining foci (predictable) and outbreaks (unpredictable) • Maximum targeting and responsiveness as malaria becomes increasingly unstable, with essential vector control and drugs	• Rapid (fire brigade) emergency responses around cases • Long-term background measures to reduce outbreak risk	• Background long-term measures to reduce outbreak risk, perhaps now with reduced scale and intensity
Weapons	• IRS and 100% coverage with ITNs (LLINs) for maximum impact	• Good epidemiology, key for targeting, and IRS for shifting targets	• Nets (including untreated) for outbreak risk, and IRS (and ITNs) for fire brigade	• Nets, with environmental measures in selected places
Vulnerabilities, threats, possible reasons for failure	• Very high-intensity transmission in equatorial Africa • Mobile populations, open houses, exophilic vectors, and inaccessible shifting foci of forest malaria in Southeast Asia and Amazon • Insecticide resistance • Conflict and complex emergencies	• Failing to follow the shifting target • Conflict and complex emergencies	• Sluggish or ineffective emergency response • Neglect of background measures • Conflict and complex emergencies	• Complacency • Conflict and complex emergencies

tion should be used to formulate a plan of action for vector control activities within the malaria elimination strategy. Another important technical aspect of the preparatory phase is mapping of the main sources of infection in the country in order to allow targeting of interventions at individual malaria foci.[12]

ATTACK PHASE

The aim of the attack phase is to interrupt transmission completely for a period long enough to allow the reservoir of infection to die out, or else to suppress the transmission to such low levels that drug-based interventions can finish the job. The attack phase starts with the selection of vector control measures and then formulation and implementation of a plan of action, which must consider the following criteria: efficacy, cost, ecological acceptability, acceptability by the local population, operational feasibility, and administrative suitability, including availability of infrastructure, trained personnel, financing, transportation, legislative support, technical direction, public information, and community participation and sustainability. For present purposes, we should stress that these issues must not be underestimated; they require investment in human, operational, and technical resources, and meticulous attention to detail.

ELIMINATION STAGES—ROOTING OUT THE LAST FOCI OF LOCAL TRANSMISSION

Sooner or later, as the general suppression of transmission proceeds, it will become clear that local transmission is no longer occurring in many places but still continues in a few remaining foci. When the target locations have been identified, vector control must be directed with great intensity, and since the targets are likely to be shifting from year to year, vector control must be capable of tracking this moving target. There are three key operational issues to evaluate:

1. How can we find and track the moving target as the foci of transmission shift and recede? This requires an excellent surveillance system, one that is active and effective even in places where other parts of the health system are weak. Creating or reinforcing such a system is a critical preparation for this phase, and its importance must not be underestimated.
2. Having detected the foci, intensive vector control must be deployed, much as in the attack phase, but there is little evidence to guide the difficult operational decisions about the extent and manner of this deployment.

3. We need to know if there is a particular reason why transmission is persisting in some places but not others. Sometimes these remnant foci reflect operational or other problems in the deployment or public acceptance of vector control, resulting in less-effective coverage in these areas. In other cases, there may be a different vector (with different behavior or with insecticide resistance) or differences in human behavior (e.g., migration patterns), so an alternative or supplementary method of vector control (e.g., adding ITNs to IRS) may be needed.

CONSOLIDATION PHASE

This is a lengthy endgame in which vigilance against reintroduction of malaria is required. At the start of this phase, the program must anticipate the possibility of reinvasion outbreaks and possible epidemics. This means remaining vigilant and being ready to respond, even after a long period of zero local cases. A robust surveillance system is needed, covering the whole population, especially the hardest-to-reach areas where outbreaks are most likely (Chapter 3). When an outbreak is detected, the response must be rapid, determined, and thorough. This is classical epidemic control, and the necessary systems and methods are essentially similar to those used to control unstable and epidemic malaria. For this purpose, IRS has particular advantages that ITNs do not share.[13]

MAINTENANCE PHASE

During this phase, the desirable characteristics of vector control activities are low intensity, with high long-term coverage, and low cost. The key concept is outbreak risk reduction. For example, the routine use of untreated nets is to be greatly encouraged: It is already a social norm in much of Southeast Asia, the Americas, Madagascar, and large areas of West Africa, and such nets give approximately half the protection of a treated net.[14] Other effective means of personal protection, such as the use of window screening, should also be encouraged. Vector control interventions that are too weak to be useful in the attack phase, such as larviciding and environmental management and especially avoidance of the creation of man-made mosquito breeding sites, may be useful to reduce the risk of reinvasion.

Perhaps the most powerful and neglected factors influencing outbreak risk are the social, economic, and environmental developments that have indirect and unintended effects on malaria transmission. For example, recent decades have seen a massive transformation in housing materials in Africa. Twenty

BOX 9.4 | How Quickly Will Malaria Return If Elimination Is Not Successful and Vector Control Stops?

The answer to this question depends on background vectorial capacity, the period for which transmission has been suppressed, the quality and capacity of the surveillance and response program, and the immune status of the human population. In Africa, where background vectorial capacity is high, the withdrawal of spraying after 3 to 5 years of intensive control led to different results in different places. In the Pare-Taveta project, malaria came back over several years, eventually reaching the original levels of endemicity, but without any excess of disease.[15] This may have been because the spraying was with the insecticide dieldrin, which has a very long active life span. After another spray trial in Kisumu, Kenya, which used the very short-acting insecticide fenitrothion, malaria is said to have returned much more quickly, with abnormally high levels of morbidity and mortality in the young children who had grown up in the sprayed area and had little immunity. A human population that has been unexposed to malaria for a substantial number of years will have little or no immunity to malaria, and reinvasion can then produce sudden epidemics that are explosive and catastrophic. This is not just a theoretical threat: Disastrous epidemics, sometimes causing hundreds of thousands of deaths, occurred after various intervals following the withdrawal of spraying in Ethiopia, Madagascar, and Sri Lanka.[16]

years ago in northern Tanzania, almost all rural houses were thatched, and corrugated iron was a luxury; now metal is becoming as common as thatch in many areas. This has a profound impact on mosquito entry and biting numbers in houses.[17, 18] The same is likely to apply to other house construction features that are spreading rapidly (e.g., ceiling boards, window shutters, concrete brick walls, cement flooring). More effort is needed to study the impact of these changes on malaria risk at the household level, and their contribution to observed trends in malaria statistics at the population level.

9.6 Operational and Technical Constraints on Vector Control

This is a selective list of issues that are either frequently encountered or strategically important and limit the present and future usefulness of vector control.

PROCUREMENT

The procurement of insecticides for IRS or the bulk purchase of LLINs is not complicated, but it is time-consuming. In the case of IRS, the amount of insecticide needed can be calculated based on previous years' consumption, with a small percentage increase to take into account new structures that may have been built. The tendering process involves a great deal of decision making and needs to be started early. Timing is critical: IRS must be performed at or just before the onset of the transmission season, and any delay greatly reduces its effectiveness. The manufacturers only start making the product after the order has been placed, and this means that lead times can be very long. Underestimation of the need to plan well in advance and order early is a common source of problems in practical vector control programs.

COMMUNITY RESISTANCE

Community involvement and acceptance of vector control measures, particularly IRS, have been cited as very important. Sometimes they are difficult to obtain, and the response may depend on the insecticide that is used. Modern house construction may offer protection against transmission, but their inhabitants often have the most resistance to spraying, especially of DDT.

FOREST MALARIA

In large forested areas of Southeast Asia, Africa, and South America, vector control is less effective than elsewhere. This is partly because of vector behavior: Vectors of forest malaria mainly rest outdoors and not in houses protected by IRS. Some tend to bite outdoors, or early in the evening, reducing the effectiveness of ITNs. Human behavior is also an important part of the challenge; often forest communities are mobile, practice shifting cultivation, move to stay in distant farms during part of the rainy season, and may be wary of outreach efforts. In many areas, the people live in houses with incomplete walls and sleep in hammocks, not beds. Forests also attract many temporary visitors. All this makes it very difficult to deliver vector control in a way that is effective.[19]

INSECTICIDE RESISTANCE—ESPECIALLY, PYRETHROID RESISTANCE

Insecticide resistance is often a key constraint limiting the sustainability of intensive insecticide-based vector control operations.[20] Experience in the 1960s and 1970s, in the first malaria eradication campaign, showed that resistance is not the most frequently encountered obstacle to effective vector control, but it is one of the most difficult to overcome.[1]

Resistance is a particularly urgent and decisive threat for ITNs because, so far, we have only one class of insecticides, the pyrethroids, that combine a safety profile suitable for use on fabric next to the skin with a rapid mode of action that kills or repels the insect before the person sleeping under the net is bitten. One form of a pyrethroid-resistant gene, *kdr*, is already widespread in West African vectors and present to a lesser extent in East Africa.[21,22] Some studies have claimed that ITNs and even IRS can still be effective despite high frequencies of this resistance gene in the local vectors,[23] but the gene is spreading rapidly and hence must confer some advantage on the insects that carry it. Even more worrying is the evidence that more-powerful metabolic mechanisms have appeared in some localities in South and West Africa.[24, 25, 26] It is hard to overestimate the strategic implications of a resistance gene that can undermine or eliminate the effectiveness of IRS and ITNs.

There are only four classes of insecticide suitable for IRS. Resistance management can be practiced using rotations or mosaics of insecticides, but a basic understanding of the underlying resistance mechanisms and the cross-resistances they produce is necessary.[27, 28] Theoretical models suggest that the most effective form of resistance management would be the use of combinations of insecticides for IRS, but this would require a great deal of development research (Chapter 10), as well as a policy change as great as that needed to establish combination drug therapies as the standard for treatment of malaria.

None of this can be managed properly without better monitoring of resistance. There has been a great deal of technical progress developing simplified methods for monitoring resistance, but these are not used nearly as widely as they should be.[20]

HUMAN RESOURCES

It was said that the Global Malaria Eradication Program "failed to eradicate malaria, but nearly succeeded in eradicating malariologists," and this is especially true for malaria entomologists. The facts are simple: global expenditure on malaria vector control is at an all-time high, but the supply of people with knowledge and skills in vector biology and control has declined steadily for the past 25 years. This has happened at all levels, from the most advanced experts to the most basic field-workers and technicians. The knowledge and skills needed for effective vector control are not especially difficult or demanding, but they are specialized, and they are no longer included in most modern courses in epidemiology, infectious disease, or tropical public health. The scarcity of these skills has emerged as one of the most important constraints on current efforts to scale up vector control, and unless the problem is tackled, it will remain a key constraint on efforts at elimination.

9.7 Conclusion

Vector control is indispensable for getting to zero transmission. Although vector control is the make-or-break intervention, there is still much to be done to maximize its effectiveness. Many forms of vector control are especially sensitive to coverage; there can be a great deal of difference between the effectiveness of 70% and 95% coverage. For elimination, the target is zero transmission, and completeness is therefore even more important than in a control setting. For the moment at least, effective technologies and the finances to pay for them are available, and the critical limiting factors are often infrastructural weakness, inadequate organizational capacity, and a scarcity of the skilled personnel needed to use these resources most effectively. The issues highlighted in this chapter illustrate the need for detailed analysis of the technical and operational obstacles to 100% coverage and effectiveness of available vector control interventions. In the longer term, there remain critical threats to the sustainability of vector control that are not yet being adequately addressed.

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