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Chapter 16

Newer Approaches for Malaria Vector Control and Challenges of Outdoor Transmission

John C. Beier, André B.B. Wilke and Giovanni Benelli

Abstract

The effective and reliable management of malaria vectors is still a global challenge. Recently, it has been noted that the first vaccine against \textit{Plasmodium falciparum} malaria, RTS,S/AS01 showed only transient protection, particularly in infants, and rapid resistance has been developing to artemisinin-based drugs. Therefore, the control of malaria mosquito vectors according to strategies of integrated vector management (IVM) is receiving emphasis. A rather wide number of novel mosquito control tools have been tested, including attractive toxic sugar baits, eave tubes, nano-synthesized pesticides loaded with microbial- and plant-borne compounds, biocontrol agents with little non-target effects, new adult repellents, oviposition deterrents, and even acoustic larvicides. However, their real-world applications remain limited. Most National Malaria Control Programs in Africa still rely on indoor residual spraying (IRS) and long-lasting insecticidal nets (LLINs) to reduce malaria incidence but generally have insufficient impact on malaria prevalence. Here, we focus on facts, trends, and current challenges in the employment of the above-mentioned vector control tools in the fight against malaria. We emphasize the needs for better vector control tools used in IVM to overcome the challenges posed by outdoor transmission and growing levels of insecticide resistance, which are threatening the efficacy of LLINs and IRS.

Keywords: Anopheles, attractive toxic sugar baits, eave tubes, long-lasting insecticidal nets, mosquito insecticide resistance, \textit{Plasmodium falciparum}, \textit{Plasmodium vivax}

1. Introduction

Malaria is a major challenge to public health; it is caused by \textit{Plasmodium} parasites, obligatorily transmitted to humans through the bites of infected female mosquitoes of the genus...
Anopheles (Diptera: Culicidae). There are five known species of Plasmodium that cause malaria in humans, *P. falciparum*, *P. vivax*, *P. ovale*, *P. malariae* and *P. knowlesi* [1–5]. Currently, 91 countries are endemic for malaria [6]. However, the African region is the most affected with 90% of the cases and 92% of deaths [7–9]. Added to that, malaria has a major impact on the economic development of these countries accounting for both direct and indirect medical costs, such as long-term disabilities and decrease in tourism [10–13].

In the past decade, two significant developments for malaria prevention and treatment were achieved. The first was the discovery of artemisinin, a very effective drug against *Plasmodium falciparum*; this molecule has been studied by the Chinese scientist Y. Tu [14–16]. The second was the development of the vaccine against *P. falciparum* (RTS,S/AS01), by GlaxoSmithKline Biologicals, the PATH Malaria Vaccine Initiative, supported by the Bill & Melinda Gates Foundation, and carried out at several African research centers [17, 18]. However, the vaccine only protected transiently the subjects against malaria [19].

Importantly, new drugs and vaccines are needed to achieve further substantial decrease in the prevalence and incidence of malaria globally and address the increasingly resistance of *Plasmodium* to the drugs currently available such as chloroquine and artemisinin [20–22]. More importantly, effective and scientific-driven control strategies for reducing *Anopheles* vector densities remain the gold standard to prevent malaria transmission [23–25]. However, controlling mosquito populations is a difficult task and is unlikely to be achieved by employing only one tool, such as the use of insecticides commonly employed in the past [26, 27]. Now it is clear that local malaria elimination across different endemic environments will not be achieved with current vector control tools, but will require using several approaches together in the form of integrated vector management (IVM) [28].

2. New tools to fight malaria vectors in an IVM perspective

To decrease the risk of vector-borne disease transmission and increase the effectiveness and sustainability of IVM in reducing mosquito populations, local features should be considered [29]. Therefore, guidelines were developed by the global vector control response (GVCR) including: (1) strengthening inter- and intra-sectoral action and collaboration; (2) enhance vector control surveillance and evaluation of interventions; (3) scale up and integrate tools and approaches; and (4) engage and mobilize communities. The goals of this initiative included increasing the effectiveness of reducing mosquito vectors for both capacity and capability as well as encouraging applied research and innovation [13].

The use of IVM aiming for optimum mosquito control contrasts with strategies used in the past that heavily relied on insecticide spraying. Current mosquito control strategies make use of every available tool. For that reason, regular assessments of local disease transmission dynamics and scientific-driven decision-making criteria are important for achieving effective vector-borne disease transmission reduction [27].

Several tools have been proposed to control vector mosquitoes, especially for the *Anopheles* genus [23, 30]. However, current malaria management programs widely rely on indoor
residual spraying (IRS), and long-lasting insecticidal nets (LLINs) [5], contrasting with contemporary IVM guidelines. Moreover, residual transmission of malaria has been commonly found using both IRS and LLINs mosquito control strategies [31]. The presence of the insecticide can be translated as a powerful selective pressure, selecting mosquitoes that are able to avoid contact with it. Key shifts in mosquito behavior such as seeking for human hosts outdoors, avoiding contact with LLINs, and finding resting places outside houses decrease the effectiveness of long-lasting insecticidal strategies [32, 33]. The efficacy of LLINs and IRS can be increased if used together with new tools and guidelines available for controlling mosquito populations, as recommended by the Vector Control Advisory Group (VCAG). Some environments are also suited for using *Bacillus thuringiensis* serovar. *israelensis* (Bti) to manage breeding sites [34–38]. Moreover, promising new tools for mosquito control are being developed, the most notable being “eave tubes” and attractive toxic sugar baits (ATSB).

Rural houses in African countries often are constructed with a gap between the walls and the roof to improve ventilation. *Anopheles* mosquitoes usually enter the houses exploiting this architectural structure exposing the residents to infective bites [39]. The “eave tubes” technology comprises the use of plastic tubes with adulticide-coated mesh under the roofline and the installation of a screen to close the remaining gap (Figure 1). When mosquitoes try to enter the house through the eaves, they come in contact with the insecticide and die. This technique is based on the attractive power that the human residents represent for the *Anopheles* mosquitoes comprising an “attract and kill” strategy (Figure 2) [40, 41]. The ATSB method is also found under the same strategy of “lure and kill”; it exploits the instinct of mosquitoes, both males and females to seek and feed on sugar sources [42, 43]. The ATBS can be deployed in bait stations or sprayed on plants and are co-formulated with low-risk toxic substances, such as boric acid [44–50]. Even though more studies and epidemiological field trials are required, “eaves tubes” and ATSB methods are leading new technologies for vector control that are highly effective, target-specific, and with minimal nontarget effects and contamination of the environment.

Several other modern strategies exploiting different approaches are being developed, including the use of cytoplasmic incompatibility caused by *Wolbachia* endosymbiotic bacteria. This
technique has been used to control *Aedes aegypti* and has achieved promising results [51]. Currently, it is undergoing field testing in Brazil and Colombia; however, further studies are needed to transfer this technology to other mosquito species since there are inherent risks for the release of mosquitoes infected with *Wolbachia*, and the result should be monitored for undesirable effects such as increased levels of West Nile virus infection observed in *Culex tarsalis* mosquitoes [52–54]. Other species of bacteria such as *Enterobacter Esp_Z* and *Chromobacterium Csp_P* have been used to inhibit the development of *Plasmodium* in mosquitoes such as *Anopheles stephensi* [55], by increasing the mosquito immune response to *Plasmodium* parasites [31, 56].

The release of irradiated sterile male mosquitoes that will seek and mate with wild females impairing the production of offspring (SIT) is once more being considered as a promising tool for controlling mosquitoes. However, its effectiveness is likely to be decreased by the presence of cryptic species and the presence of multiple *Anopheles* vectors. The same issue should be considered with the use of genetically modified mosquitoes carrying a lethal gene (RIDL), since this technique is species specific and may not be indicated to control outdoor malaria transmission. Genetically modified mosquito techniques based on impairing the *Plasmodium* life cycle inside the mosquito is still in preliminary phases of development and is not likely to be available in the near future [30, 57–61].

The above strategies can be used in the IVM context along with well-established control tools, such as selective microbial and plant-borne pesticides effective against immature mosquitoes, oviposition deterrents, insecticide-coated clothes and other surfaces for personal protection, spatial repellents reducing human-vector contact such as microencapsuled insecticide paint formulation, as well as synthetic and plant-borne repellents [23, 62–69].

The development of plant-based larvicides is of particular interest, and several plant species were successfully used for the synthesis of nano-mosquitocides; nonetheless, plant-based
ovicidal and ovideterrent products are still scarce. This technology can provide rapid synthesis of toxic substances and mosquito repellents useful to manage mosquito populations, with minimal toxicity to humans. Even though mosquito control strategies relying on plant-based larvicides are a fast-growing research area, it is still in the preliminary phase of development and several steps should be taken into account, that is, (1) development, characterization, and optimization of potential botanical components suitable for nano-biosynthesis; (2) identification of potential toxic nanoparticles; (3) feasibility of utilization of plant-based industrial by-products as nano-mosquitocides; (4) field evaluation of the effectiveness of plant-based nanoparticles to control mosquito populations; and (5) effect of plant-based nanoparticles on non-target species and environment [70, 71].

Natural predators also have been used to control immature mosquitoes including cyclopoid copepods, Toxorhynchites mosquitoes, water bugs, backswimmers, tadpoles, and fishes [72–74]. The efficacy of mosquito predators may vary accordingly to different environmental settings and their impact on non-target aquatic species and difficulty in using multiple or artificial breeding containers should be considered for their use in control strategies [71, 75]. Another approach for controlling mosquitoes is based on endectocide ivermectin, a molecule that has been used for more than 30 years to control lymphatic filariasis. This molecule remains in the human bloodstream following a standard oral dose and can kill Anopheles mosquitoes that feed on the blood of medicated persons [76–79]. Controlling vector mosquito populations is a difficult task and so the addition of new technologies to be considered for IVM will help improve the effectiveness of vector-borne disease transmission [80–83].

Current strategies for malaria vector control used in most African countries still rely on LLINs and IRS, which generally are not sufficient to achieve successful malaria control and local elimination [13, 25, 84]. Even though LLINs and IRS are very effective for in-house reduction of malaria transmission, in endemic areas, it has been showed that insecticide-treated bed nets reduce malaria prevalence only by 13% [85–91]. Furthermore, due to the high abundance of mosquitoes, even low levels of Plasmodium transmission undermine efforts to reduce the prevalence of malaria, since human hosts are bitten multiple times increasing the chance of coming in contact with the parasite. The prevalence of *P. falciparum* is strongly related to the number of infective bites per person per year or annual entomological inoculation rates (EIRs), ranging from <1 to >500. Malaria prevalence is positively associated with high EIRs; however, even low annual EIRs (<5) can be associated with malaria prevalence levels of 40–60%. For a significant reduction in the prevalence of malaria, EIRs must be lower than 1 [92]. Vector control strategies implemented in Africa have so far been unable to achieve such low levels of malaria transmission [93].

Besides, with the increase in the control efforts focused into indoor mosquitoes, the dynamics of malaria transmission is shifting from the highly endophilic to more exophilic outdoor-adapted species within the *Anopheles gambiae* complex [94–99]. In Asia, the main malaria vectors of the *Anopheles dirus* complex are exophagic and difficult to target with conventional control strategies [31]. Moreover, increasing resistance to insecticides renders LLINs and IRS less effective for controlling *Anopheles* populations. As well, even though larvicides are effective against immature mosquitoes, they are not recommended for application in rural areas [100–105].
3. Conclusions and issues to watch for

The importance of basic knowledge on mosquito vector behavior and ecology for the development of tailor-made vector control strategies is considered key in the recent WHO Health and Environment Linkages Initiative (HELI), highlighting its importance for sustainable long-term mosquito control actions [106–111].

Recently, an updated research agenda for malaria elimination and eradication (malERA) was published [26, 112–114]. It comprises a multidisciplinary approach to the most important challenges of controlling malaria. Several factors significantly impact the dynamics of malaria transmission. Specifically, shifts in mosquito ecology and behavior caused by anthropogenic alterations in the environment have a major impact on the effectiveness of control strategies. These alterations include, but not limited to, urbanization, human movement, availability of breeding containers and water bodies, hosts for blood feeding and availability of sugar sources and resting places. Moreover, mosquito insecticide resistance, behavioral avoidance, high vector biodiversity, competitive and food web interactions, mosquito population dynamics and dispersion also play a major role in the complex scenario comprising the dynamics of malaria transmission [17, 115, 116].

The development of reliable and effective mosquito control strategies is no easy task, and several challenges must be overcome to achieve a long-term sustainable reduction of mosquito populations. Most of the new strategies and tools developed for controlling vector mosquito populations are not rigorously tested, and most of the time, their real epidemiological impact is not properly assessed rendering the deployment of ineffective mosquito control strategies with limited result on the prevalence of vector-borne diseases [117]. These challenges can be classified as systemic, structural, informational, environmental, human movement, political and financial ones [13]. Key core issues have to be addressed in order to decrease the prevalence of malaria, such as (1) vector surveillance is often neglected or insufficient in most countries at risk of mosquito-borne diseases, rendering control efforts ineffective; (2) malaria endemic countries are often endemic for more than one major mosquito-borne disease depleting the availability of resources; (3) there is a lack of scientific evidence to guide the efforts for mosquito control; (4) anthropogenic alterations in the environment and global warming are responsible for driving the abundance of vector mosquitoes, directly affecting the effectiveness of control strategies; (5) the increase in the human population and movement of people is associated with the dispersion of vector mosquitoes, exposing non-immune populations to new diseases; and (6) funds for vector surveillance are negligible and even though financial support has been made available for LLINs and IRS for controlling *Anopheles* mosquitoes, other vector-borne diseases are largely neglected [13, 17, 118, 119].

Priorities in vector control should be defined by the national vector-borne disease control program and studies designed and performed in consultation with national and international experts in the relevant field. The plan should consider a list of strategic key areas necessary to implement vector control in a given country, followed by research guidance from academic institutes and companies [27]. The most important topics to be considered that are also in agreement with the WHO criteria, comprise: (1) assessment of the health system limitations to improve processes and methods aiming for the improvement in efficacy of vector control; (2) implementation
of mosquito surveillance for the development of guidelines and models of the risk of disease transmission (Figure 3); (3) development of effective and environmentally friendly strategies to reduce malaria and other vector-borne disease transmission, following the recommendations by VCAG and considering the increase of insecticide resistance [100, 102]. To our understanding, traditional insecticide-based control efforts, such as IRS and LLIN, should be used in combination with novel eco-friendly tools, such as “eave tubes technology,” ATSB methods, and even the employment of the ectendocide ivermectin [40, 44, 76]. These new mosquito control tools should be accompanied by (4) an evaluation of their effectiveness, assessment of their usefulness and impact through randomized controlled trials with entomological and epidemiological outcomes (Figure 3), this has been done for traditional control strategies such as LLINs and IRS; (5) the monitoring of man-made alteration in the environment and its impact in the dynamics of malaria vectors; and (6) the establishment of a multi-disciplinary team with different areas of expertise (Figure 3) [100, 102, 120]. Indeed, the transdisciplinary cooperation among professionals is important for ensuring adequate evaluation of the epidemiological impact triggered by novel mosquito vector control strategies.

Here we illustrate the complex scenario comprising the epidemiology of malaria and how anthropogenic selective pressures are modulating the ecology and behavior of vector mosquitoes. To our understanding, there is no other choice rather to use rigorous, science-driven strategies for controlling vector mosquito populations.

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Author details

John C. Beier*, André B.B. Wilke1 and Giovanni Benelli2,3
*Address all correspondence to: jbeier@med.miami.edu

1 Department of Public Health Sciences, University of Miami Miller School of Medicine, Miami, FL, United States
2 Department of Agriculture, Food and Environment, University of Pisa, Pisa, Italy
3 The BioRobotics Institute, Sant’Anna School of Advanced Studies, Pisa, Italy

References

[1] Aly ASI, Vaughan AM, Kappe SHI. Malaria parasite development in the mosquito and infection of the mammalian host. Annual Review of Microbiology. 2009;63:195-221
[2] Beier JC. Malaria parasite development in mosquitoes. Annual Review of Entomology. 1998;43:519-543
[3] Capanna E. Grassi versus Ross: Who solved the riddle of malaria? International Microbiology. 2006;9:69-74
[4] Hempelmann E, Krafts K. Bad air, amulets and mosquitoes: 2,000 years of changing perspectives on malaria. Malaria Journal. 2013;12:232
[5] WHO. Malaria Fact Sheet. 2017. (Updated April 2017)
[6] WHO. World Malaria Report 2017. Available at: http://www.who.int/malaria/publications/world-malaria-report-2015/report/en/Malaria report 2017
[7] White NJ. Declining malaria transmission and pregnancy outcomes in southern Mozambique. The New England Journal of Medicine. 2015;373:1670-1671
[8] Bhatt S, Weiss DJ, Cameron E, Bisanzio D, Mappin B, Dalrymple U, et al. The effect of malaria control on Plasmodium falciparum in Africa between 2000 and 2015. Nature. 2015;526:207-211
[9] White MT, Conteh L, Cibulskis R, Ghanir AC. Costs and cost-effectiveness of malaria control interventions - A systematic review. Malaria Journal. 2011;10:337
[10] Sachs J, Malaney P. The economic and social burden of malaria. Nature. 2002;415:680-685
[11] Gallup JL, Sachs JD. The economic burden of malaria. The American Journal of Tropical Medicine and Hygiene. 2001;64:85-96

[12] Malaney P, Spielman A, Sachs J. The malaria gap. The American Journal of Tropical Medicine and Hygiene. 2004;71:141-146

[13] WHO. Global Vector Control Response 2017-2030; 2017

[14] Tu Y. The discovery of artemisinin (qinghaosu) and gifts from Chinese medicine. Nature Medicine. 2011;17:1217-1220

[15] Callaway E, Cyranoski D. Anti-parasite drugs sweep Nobel prize in medicine 2015. Nature. 2015;526:174-175

[16] Su X-Z, Miller LH. The discovery of artemisinin and the Nobel prize in physiology or medicine. Science China. Life Sciences. 2015;58:1175-1179

[17] Benelli G, Mehlhorn H. Declining malaria, rising of dengue and Zika virus: Insights for mosquito vector control. Parasitology Research. 2016;115:1747-1754

[18] WHO. Background Brief: Malaria Vaccine RTS,S/AS01; 2015. (Updated 23 October 2015)

[19] Gosling R, von Seidlein L. The future of the RTS,S/AS01 malaria vaccine: An alternative development plan. PLoS Medicine. 2016;13:1-6

[20] Jensen M, Mehlhorn H. Seventy-five years of Resochin® in the fight against malaria. Parasitology Research. 2009;105:609-627

[21] Burrows JN, Duparc S, Gutteridge WE, van Huijstuijnen RH, Kaszubska W, Macintyre F, et al. New developments in anti-malarial target candidate and product profiles. Malaria Journal. BioMed Central. 2017;16:151

[22] WHO. Updates on Artemisinin Resistance; 2016. (Updated 6 October 2016)

[23] Benelli G. Research in mosquito control: Current challenges for a brighter future. Parasitology Research. 2015;114:2801-2805

[24] Chanda E, Amineshewa B, Bagayoko M, Goreve JM, Macdonald MB. Harnessing integrated vector management for enhanced disease prevention. Trends in Parasitology. 2017;33:30-41

[25] Hemingway J, Shretta R, Wells TNC, Bell D, Djimdé AA, Achée N, et al. Tools and strategies for malaria control and elimination: What do we need to achieve a grand convergence in malaria? PLoS Biology. 2016;14:1-14

[26] Nájera JA, González-Silva M, Alonso PL. Some lessons for the future from the global malaria eradication programme (1955-1969). PLoS Medicine. 2011;8:e1000412

[27] WHO. Health and Environment Linkages Initiative – HELI priority environment and health risks; 2017. (www.who.int/heli/risks/vectors/malariacontrol/en/index3.html)

[28] Lizzi KM, Qualls WA, Brown SC, Beier JC. Expanding integrated vector management to promote healthy environments. Trends in Parasitology. 2014;30:394-400
[29] WHO. Handbook for integrated vector management. Outlooks on Pest Management. 2013;24:142-143

[30] Bourtzis K, Lees RS, Hendrichs J, Vreysen MJ. More than one rabbit out of the hat: Radiation, transgenic and symbiont-based approaches for sustainable management of mosquito and tsetse fly populations. Acta Tropica. 2016;157:115-130

[31] Durnez L, Coosemans M. Residual transmission of malaria: An old issue for new approaches. In: Manguin S, editor. Anopheles Mosquitoes–New Insights into Malaria Vectors. Rijeka: InTech Open Access; 2013. DOI: 10.5772/55925

[32] Killeen GF, Chitnis N. Potential causes and consequences of behavioural resilience and resistance in malaria vector populations: A mathematical modelling analysis. Malaria Journal. 2014;13:97

[33] Killeen GF, Govella NJ, Lwetoijera DW, Okumu FO. Most outdoor malaria transmission by behaviourally-resistant Anopheles arabiensis is mediated by mosquitoes that have previously been inside houses. Malaria Journal. BioMed Central. 2016;15:225

[34] Bravo A, Gill SS, Soberón M. Mode of action of Bacillus thuringiensis cry and Cyt toxins and their potential for insect control. Toxicon. 2007;49:423-435

[35] Boyce R, Lenhart A, Kroeger A, Velayudhan R, Roberts B, Horstick O. Bacillus thuringiensis israelensis (Bti) for the control of dengue vectors: Systematic literature review. Tropical Medicine & International Health. 2013;18:564-577

[36] Pavela R. Essential oils for the development of eco-friendly mosquito larvicides: A review. Industrial Crops and Products. 2015;76:174-187

[37] Lacey LA. Bacillus thuringiensis serovariety israelensis and Bacillus sphaericus for mosquito control. Journal of the American Mosquito Control Association. 2007;23:133-163

[38] WHO. Vector Control Advisory Group (VCAG) on New Paradigms; 2017. Available at: http://www.who.int/neglected_diseases/vector_ecology/VCAG/en/

[39] Knols BGJ, Farenhorst M, Andriessen R, Snetselaar J, Suer RA, Osinga AJ, et al. Eave tubes for malaria control in Africa: An introduction. Malaria Journal. 2016;15:404

[40] Sternberg ED, Ng’habi KR, Lyimo IN, Kessy ST, Farenhorst M, Thomas MB, et al. Eave tubes for malaria control in Africa: Initial development and semi-field evaluations in Tanzania. Malaria Journal. 2016;15:447

[41] Waite JL, Lynch PA, Thomas MB. Eave tubes for malaria control in Africa: A modelling assessment of potential impact on transmission. Malaria Journal. 2016;15:449

[42] Beier JC, Muller GC, Gu W, Arheart KL, Schlein Y. Attractive toxic sugar bait (ATSB) methods decimate populations of Anopheles malaria vectors in arid environments regardless of the local availability of favoured sugar-source blossoms. Malaria Journal. 2012;11:31
[43] Allan SA. Susceptibility of adult mosquitoes to insecticides in aqueous sucrose baits. Journal of Vector Ecology. 2011;36:59-67

[44] Müller GC, Beier JC, Traore SF, Toure B, Traore MM, Bah S, et al. Successful field trial of attractive toxic sugar bait (ATSB) plant-spraying methods against malaria vectors in the *Anopheles gambiae* complex in Mali, West Africa. Malaria Journal. 2010;9:210

[45] Naranjo DP, Qualls WA, Müller GC, Samson DM, Roque D, Alimi T, et al. Evaluation of boric acid sugar baits against *Aedes albopictus* (Diptera: Culicidae) in tropical environments. Parasitology Research. 2013;112:1583-1587

[46] Stewart ZP, Oxborough RM, Tungu PK, Kirby MJ, Rowland MW, Irish SR. Indoor application of attractive toxic sugar bait (ATSB) in combination with mosquito nets for control of pyrethroid-resistant mosquitoes. PLoS One. 2013;8:6-12

[47] Xue R-D, Mueller GC, Kline DL, Barnard DR, Müller GC, Kline DL, et al. Effect of application rate and persistence of boric acid sugar baits applied to plants for control of *Aedes albopictus*. Journal of the American Mosquito Control Association. 2011;27:56-60

[48] Xue R-D, Ali A, Kline DL, Barnard DR. Field evaluation of boric acid- and fipronil-based bait stations against adult mosquitoes. Journal of the American Mosquito Control Association. 2008;24:415-418

[49] Xue R-D, Kline DL, Ali A, Barnard DR. Application of boric acid baits to plant foliage for adult mosquito control. Journal of the American Mosquito Control Association. 2006;22:497-500

[50] Müller GC, Kravchenko VD, Schlein Y. Decline of *Anopheles sergentii* and *Aedes caspius* populations following presentation of attractive toxic (spinosad) sugar bait stations in an oasis. Journal of the American Mosquito Control Association. 2008;24:147-149

[51] Walker T, Johnson PH, Moreira LA, Iturbe-Ormaetxe I, Frentiu FD, McMeniman CJ, et al, The wMel Wolbachia strain blocks dengue and invades caged *Aedes aegypti* populations. Nature. 2011;476:450-453

[52] Aliota MT, Walker EC, Uribe Yepes A, Dario Velez I, Christensen BM, Osorio JE. The wMel strain of *Wolbachia* reduces transmission of chikungunya virus in *Aedes aegypti*. PLoS Neglected Tropical Diseases. 2016;10:e0004677

[53] Callaway E. Rio fights Zika with biggest release yet of bacteria-infected mosquitoes. Nature. 2016;539:17-18

[54] Dodson BL, Hughes GL, Paul O, Matacchiero AC, Kramer LD, Rasgon JL. *Wolbachia* enhances West Nile virus (WNV) infection in the mosquito *Culex tarsalis*. PLoS Neglected Tropical Diseases. 2014;8:e2965

[55] Eappen AG, Smith RC, Jacobs-Lorena M. Enterobacter-activated mosquito immune responses to *Plasmodium* involve activation of SRPN6 in *Anopheles stephensi*. PLoS One. 2013;8:e62937

Newer Approaches for Malaria Vector Control and Challenges of Outdoor Transmission
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397
[56] Ramirez JL, Short SM, Bahia AC, Saraiva RG, Dong Y, Kang S, et al. *Chromobacterium Csp_P* reduces malaria and dengue infection in vector mosquitoes and has entomopathogenic and in vitro anti-pathogen activities. PLoS Pathogens. 2014;10:e1004398

[57] Ito J, Ghosh A, Moreira L, Wimmer E, Jacobs-Lorena M. Transgenic anopheline mosquitoes impaired in transmission of a malaria parasite. Nature. 2002;417:452-455

[58] Wiwatanaratanabutr I, Allan S, Linthicum K, Kittayapong P. Strain-specific differences in mating, oviposition, and host-seeking behavior between *Wolbachia*-infected and uninfected *Aedes albopictus*. Journal of the American Mosquito Control Association. 2010;26:265-273

[59] Oliva CF, Jacquet M, Gilles J, Lemperiere G, Maquart PO, Quilici S, et al. The sterile insect technique for controlling populations of *Aedes albopictus* (Diptera: Culicidae) on Reunion Island: Mating vigour of sterilized males. PLoS One. 2012;7:1-8

[60] Oliva CF, Damiens D, Vreysen MJB, Lemperière G, Gilles J. Reproductive strategies of *Aedes albopictus* (Diptera: Culicidae) and implications for the sterile insect technique. PLoS One. 2013;8:e78884

[61] Bouyer J, Lefrançois T. Boosting the sterile insect technique to control mosquitoes. Trends in Parasitology. 2014;30:271-273

[62] Pavela R, Benelli G. Essential oils as ecofriendly biopesticides? Challenges and constraints. Trends in Plant Science. 2016;21:1000-1007

[63] Pavela R. Encapsulation—A convenient way to extend the persistence of the effect of ecofriendly mosquito larvicides. Current Organic Chemistry. 2016;20:2674-2680

[64] Xue R-D, Barnard DR, Ali A. Laboratory and field evaluation of insect repellents as oviposition deterrents against the mosquito *Aedes albopictus*. Medical and Veterinary Entomology. 2001;15:126-131

[65] Benelli G. Green synthesized nanoparticles in the fight against mosquito-borne diseases and cancer—A brief review. Enzyme and Microbial Technology. 2016;95:58-68

[66] Rajaganesh R, Murugan K, Panneerselvam C, Jayashanthini S, Aziz AT, Roni M, et al. Fern-synthesized silver nanocrystals: Towards a new class of mosquito oviposition deterrents? Research in Veterinary Science. 2016;109:40-51

[67] Banks SD, Murray N, Wilder-Smith A, Logan JG. Insecticide-treated clothes for the control of vector-borne diseases: A review on effectiveness and safety. Medical and Veterinary Entomology. 2014;28:14-25

[68] Achee NL, Bangs MJ, Farlow R, Killeen GF, Lindsay S, Logan JG, et al. Spatial repellents: From discovery and development to evidence-based validation. Malaria Journal. 2012;11:164

[69] Mosqueira B, Soma DD, Namountougou M, Poda S, Diabaté A, Ali O, et al. Pilot study on the combination of an organophosphate-based insecticide paint and pyrethroid-treated
long lasting nets against pyrethroid resistant malaria vectors in Burkina Faso. Acta Tropica. 2015;148:162-169

[70] Benelli G. Plant-mediated biosynthesis of nanoparticles as an emerging tool against mosquitoes of medical and veterinary importance: A review. Parasitology Research. 2016;115:23-34

[71] Benelli G, Jeffries C, Walker T. Biological control of mosquito vectors: Past, present, and future. Insects. 2016;7:52

[72] Marten GG, Bordes ES, Nguyen M. Use of Cyclopoid Copepods for Mosquito Control. Ecology and Morphology of Copepods. Dordrecht: Springer Netherlands; 1994. pp. 491-496

[73] Bowatte G, Perera P, Seneviratne G, Meegaskumbura S, Meegaskumbura M. Tadpoles as dengue mosquito (Aedes aegypti) egg predators. Biological Control. 2013;67:469-474

[74] Murugan K, Benelli G, Panneerselvam C, Subramaniam J, Jeyalalitha T, Dinesh D, et al. Cymbopogon citratus-synthesized gold nanoparticles boost the predation efficiency of copepod Mesocyclops aspericornis against malaria and dengue mosquitoes. Experimental Parasitology. 2015;153:129-138

[75] Walshe DP, Garner P, Abdel-Hameed Adeel AA, Pyke GH, Burkot T. Larvivorous fish for preventing malaria transmission. In: Burkot T, editor. Cochrane Database of Systematic Reviews. Chichester, UK: John Wiley & Sons, Ltd; 2013

[76] Ōmura S, Crump A. Ivermectin and malaria control. Malaria Journal. 2017;16:172

[77] Chaccour C, Rabinovich NR. Ivermectin to reduce malaria transmission II. Considerations regarding clinical development pathway. Malaria Journal. 2017;16:166

[78] Chaccour C, Rabinovich NR. Ivermectin to reduce malaria transmission III. Considerations regarding regulatory and policy pathways. Malaria Journal. 2017;16:162

[79] Chaccour C, Hammann F, Rabinovich NR. Ivermectin to reduce malaria transmission I. Pharmacokinetic and pharmacodynamic considerations regarding efficacy and safety. Malaria Journal. 2017;16:161

[80] Beier JC, Keating J, Githure JJ, Macdonald MB, Impoinvil DE, Novak RJ. Integrated vector management for malaria control. Malaria Journal. 2008;7:54

[81] WHO. Global Strategic Framework for Integrated Vector Management; 2004. (In WHO/CDS/CPE/PVC/2004. pp. 12)

[82] WHO. Report of the WHO Consultation on Integrated Vector Management (IVM). World Health Organization, Geneva; 2007

[83] WHO. Handbook on Integrated Vector Management. Geneva: World Health Organization; 2012

[84] WHO. Malaria Vector Control and Personal Protection; 2006. WHO Technical Report Series No 936
[85] Lengeler C. Insecticide-treated bed nets and curtains for preventing malaria. In: Lengeler C, editor. Cochrane Database of Systematic Reviews. Chichester, UK: John Wiley & Sons, Ltd; 2004. p. CD000363

[86] Pluess B, Tanser FC, Lengeler C, Sharp BL. Indoor residual spraying for preventing malaria. In: Lengeler C, editor. Cochrane Database of Systematic Reviews. Chichester, UK: John Wiley & Sons, Ltd; 2010. p. CD006657

[87] Bhattarai A, Ali AS, Kachur SP, Mårtensson A, Abbas AK, Khatib R, et al. Impact of Artemisinin-based combination therapy and insecticide-treated nets on malaria burden in Zanzibar. PLoS Medicine. 2007;4:e309

[88] Kleinschmidt I, Torrez M, Schwabe C, Benavente L, Seocharan I, Jituboh D, et al. Factors influencing the effectiveness of malaria control in Bioko Island, Equatorial Guinea. The American Journal of Tropical Medicine and Hygiene. 2007;76:1027-1032

[89] Keating J, Locatelli A, Gebremichael A, Ghebremeskel T, Mufunda J, Mihreteab S, et al. Evaluating indoor residual spray for reducing malaria infection prevalence in Eritrea: Results from a community randomized control trial. Acta Tropica. 2011;119:107-113

[90] Protopopoff N, Van Bortel W, Marcotty T, Van Herp M, Maes P, Baza D, et al. Spatial targeted vector control is able to reduce malaria prevalence in the highlands of Burundi. The American Journal of Tropical Medicine and Hygiene. 2008;79:12-18

[91] WHO. Global Malaria Control and Elimination: Report of a Technical Review. Geneva: World Health Organization; 2008

[92] Killeen GF, Githure JI, Beier JC. Short report: Entomologic inoculation rates and Plasmodium falciparum malaria prevalence in Africa. The American Journal of Tropical Medicine and Hygiene. 1999;61:109-113

[93] Shaukat AM, Breman JG, McKenzie FE. Using the entomological inoculation rate to assess the impact of vector control on malaria parasite transmission and elimination. Malaria Journal. 2010;9:122

[94] Killeen GF. Characterizing, controlling and eliminating residual malaria transmission. Malaria Journal. 2014;13:330

[95] Bayoh MN, Mathias DK, Odiere MR, Mutuku FM, Kamau L, Gimnig JE, et al. Anopheles gambiae: Historical population decline associated with regional distribution of insecticide-treated bed nets in western Nyanza Province, Kenya. Malaria Journal. 2010;9:62

[96] Norris DE, Glass GE, Norris LC, Fornadel CM. Analysis of Anopheles arabiensis blood feeding behavior in southern Zambia during the two years after introduction of insecticide-treated bed nets. The American Journal of Tropical Medicine and Hygiene. 2010;83:848-853

[97] Russell TL, Govella NJ, Azizi S, Drakeley CJ, Kachur SP, Killeen GF. Increased proportions of outdoor feeding among residual malaria vector populations following increased use of insecticide-treated nets in rural Tanzania. Malaria Journal. 2011;10:80
[98] Derua YA, Alifrangis M, Hosea KM, Meyrowitsch DW, Magesa SM, Pedersen EM, et al. Change in composition of the Anopheles gambiae complex and its possible implications for the transmission of malaria and lymphatic filariasis in North-Eastern Tanzania. Malaria Journal. 2012;11:188

[99] Mwangangi JM, Mbogo CM, Orindi BO, Muturi EJ, Midega JT, Nzovu J, et al. Shifts in malaria vector species composition and transmission dynamics along the Kenyan coast over the past 20 years. Malaria Journal. 2013;12:13

[100] Naqqash MN, Gökçe A, Bakhsh A, Salim M. Insecticide resistance and its molecular basis in urban insect pests. Parasitology Research. 2016;115:1363-1373

[101] Tabashnik BE. Evolution of resistance to Bacillus thuringiensis. Annual Review of Entomology. 1994;39:47-79

[102] Hemingway J, Ranson H. Insecticide resistance in insect vectors of human disease. Annual Review of Entomology. 2000;45:371-391

[103] Enayati A, Hemingway J. Malaria management: past, present, and future. Annual Review of Entomology. 2010;55:569-591

[104] Ranson H, N’Guessan R, Lines J, Moiroux N, Nkuni Z, Corbel V. Pyrethroid resistance in African anopheline mosquitoes: What are the implications for malaria control? Trends in Parasitology. 2009;27:91-98

[105] Ranson H, Abdallah H, Badolo A, Guelbeogo W, Kerah-Hinzoumbé C, Yangalbé-Kalnoné E, et al. Insecticide resistance in Anopheles gambiae: Data from the first year of a multi-country study highlight the extent of the problem. Malaria Journal. 2009;8:299

[106] Charlwood JD, Pinto J, Sousa CA, Ferreira C, Do RVE. Male size does not affect mating success (of Anopheles gambiae in Sao Tome). Medical and Veterinary Entomology. 2002;16:109-111

[107] Cabrera M, Jaffe K. An aggregation pheromone modulates lekking behavior in the vector mosquito Aedes aegypti (Diptera: Culicidae). Journal of the American Mosquito Control Association. 2007;23:1-10

[108] Dabiré KR, Sawadogo PS, Hien DF, Bimbilé-Somda NS, Soma DD, Millogo A, et al. Occurrence of natural Anopheles arabiensis swarms in an urban area of Bobo-Dioulasso city, Burkina Faso, West Africa. Acta Tropica. 2014;132:S35-S41

[109] Diabaté A, Yaro AS, Dao A, Diallo M, Huestis DL, Lehmann T. Spatial distribution and male mating success of Anopheles gambiae swarms. BMC Evolutionary Biology. 2011;11:184

[110] Pitts RJ, Mozūraitis R, Gauvin-Bialecki A, Lempérière G. The roles of kairomones, synomones and pheromones in the chemically-mediated behaviour of male mosquitoes. Acta Tropica. 2014;132:S26-S34

[111] Oliveira-Ferreira J, Lacerda MV, Brasil P, Ladislau JL, Tauil PL, Daniel-Ribeiro CT. Malaria in Brazil: An overview. Malaria Journal. 2010;9:115
[112] malERA Refresh Consultative Panel on Health Systems and Policy Research. malERA: An updated research agenda for combination interventions and modeling in malaria elimination and eradication. PLoS Medicine. 2017;14:e1002453

[113] Rabinovich RN, Drakeley C, Djimde AA, Fenton Hall B, Hay SI, Hemingway J, et al. malERA: An updated research agenda for malaria elimination and eradication. PLoS Medicine. 2017;14:e1002456

[114] malERA Refresh Consultative Panel on Tools for Malaria Elimination. malERA: An updated research agenda for diagnostics, drugs, vaccines, and vector control in malaria elimination and eradication. PLoS Medicine. 2017;14:e1002455

[115] Lemon SM, Sparling F, Hamburg MA, Relman DA, Choffnes ER, Mack A. Vector-borne diseases: Understanding the environmental, human health, and ecological connections, Workshop Summary. 2008. Available at: http://www.ncbi.nlm.nih.gov/pubmed/21452451

[116] Ferguson HM, Dornhaus A, Beeche A, Borgemeister C, Gottlieb M, Mulla MS, et al. Ecology: A prerequisite for malaria elimination and eradication. PLoS Medicine. 2010;7:1-7

[117] Wilson AL, Boelaert M, Kleinschmidt I, Pinder M, Scott TW, Tusting LS, et al. Evidence-based vector control? Improving the quality of vector control trials. Trends in Parasitology. 2015;31:380-390

[118] Becker N, Pluskota B, Kaiser A, Schaffner F. Exotic Mosquitoes Conquer the World. In: Mehlhorn H, editor. Arthropods as Vectors of Emerging Diseases. Parasitology Research Monographs. Berlin, Heidelberg: Springer; 2012;3:31-60. DOI: https://doi.org/10.1007/978-3-642-28842-5_2

[119] Sinka ME, Bangs MJ, Manguin S, Rubio-palis Y, Chareonviriyaphap T, Coetzee M, et al. A global map of dominant malaria vectors. Parasites & Vectors. 2012;5:69

[120] Benelli G, Beier JC. Current vector control challenges in the fight against malaria. Acta Tropica. 2017;174:91-96