Effectiveness of a long-lasting piperonyl butoxide-treated insecticidal net and indoor residual spray interventions, separately and together, against malaria transmitted by pyrethroid-resistant mosquitoes: a cluster, randomised controlled, two-by-two factorial design trial

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Summary

Background Progress in malaria control is under threat by wide-scale insecticide resistance in malaria vectors. Two recent vector control products have been developed: a long-lasting insecticidal net that incorporates a synergist piperonyl butoxide (PBO) and a long-lasting indoor residual spraying formulation of the insecticide pirimiphos-methyl. We evaluated the effectiveness of PBO long-lasting insecticidal nets versus standard long-lasting insecticidal nets as single interventions and in combination with the indoor residual spraying of pirimiphos-methyl.

Methods We did a four-group cluster randomised controlled trial using a two-by-two factorial design of 48 clusters derived from 40 villages in Muleba (Kagera, Tanzania). We randomly assigned these clusters using restricted randomisation to four groups: standard long-lasting insecticidal nets, PBO long-lasting insecticidal nets, standard long-lasting insecticidal nets plus indoor residual spraying, or PBO long-lasting insecticidal nets plus indoor residual spraying. Both standard and PBO nets were distributed in 2015. Indoor residual spraying was applied only once in 2015. We masked the inhabitants of each cluster to the type of nets received, as well as field staff who took blood samples. Neither the investigators nor the participants were masked to indoor residual spraying. The primary outcome was the prevalence of malaria infection in children aged 6 months to 14 years assessed by cross-sectional surveys at 4, 9, 16, and 21 months after intervention. The endpoint for assessment of indoor residual spraying was 9 months and PBO long-lasting insecticidal nets was 21 months. This trial is registered with ClinicalTrials.gov, number NCT02288637.

Findings 7184 (68·0%) of 10 560 households were selected for post-intervention survey, and 15 469 (89·0%) of 17 377 eligible children from the four surveys were included in the intention-to-treat analysis. Of the 878 households visited in the two indoor residual spraying groups, 827 (94%) had been sprayed. Reported use of long-lasting insecticidal nets, across all groups, was 15% since recommended to increase coverage of PBO long-lasting insecticidal nets. Long-lasting insecticidal nets alone or standard long-lasting insecticidal nets plus indoor residual spraying. Both standard and PBO nets were distributed in 2015. Indoor residual spraying was applied only once in 2015. We masked the inhabitants of each cluster to the type of nets received, as well as field staff who took blood samples. Neither the investigators nor the participants were masked to indoor residual spraying. The primary outcome was the prevalence of malaria infection in children aged 6 months to 14 years assessed by cross-sectional surveys at 4, 9, 16, and 21 months after intervention. The endpoint for assessment of indoor residual spraying was 9 months and PBO long-lasting insecticidal nets was 21 months. This trial is registered with ClinicalTrials.gov, number NCT02288637.

Interpretation The PBO long-lasting insecticidal net and non-pyrethroid indoor residual spraying interventions showed improved control of malaria transmission compared with standard long-lasting insecticidal nets where pyrethroid resistance is prevalent and either intervention could be deployed to good effect. As a result, WHO has recommended to increase coverage of PBO long-lasting insecticidal nets. Combining indoor residual spraying with pirimiphos-methyl and PBO long-lasting insecticidal nets provided no additional benefit compared with PBO long-lasting insecticidal nets alone or standard long-lasting insecticidal nets plus indoor residual spraying.

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Introduction

Long-lasting insecticidal nets and indoor residual spraying are the cornerstones of malaria control in sub-Saharan Africa. Together with effective treatment, these interventions are estimated to have globally reduced malaria morbidity by 41% and mortality by 62% between 2000 and 2015. Despite this public health success, recent wide-scale selection of insecticide resistance in the mosquito vectors across Africa threatens to reverse the present gains. Development and evaluation of new strategies and tools are needed to address the threat of resistance and will accelerate progress towards elimination.

The range of insecticides available for indoor residual spraying is limited. For long-lasting insecticidal nets, the range is particularly restricted because pyrethroids are the only class of insecticides recommended by WHO for nets. Evidence from indoor residual spraying programmes suggests that pyrethroid resistance can contribute to operational control failure—eg, in South Africa, control was only restored once the pyrethroid was replaced by an insecticide to which vectors were susceptible. By contrast, the negative effect of pyrethroid resistance on the effectiveness of long-lasting insecticidal nets has been less clear and harder to quantify than indoor residual spraying. Although entomological evidence suggests that these nets are becoming less effective at killing mosquitoes in household conditions when resistance develops, the physical barrier provided by the net,
especially when new and intact, might mitigate some of the loss in bioefficacy due to resistance. Cohort studies have shown that long-lasting insecticidal nets remain protective against malaria infection in areas of moderate insecticide resistance in Malawi and Kenya, whereas no reduction in incidence was observed after the distribution of these nets in Uganda.

Anticipating the possible failure of current control tools due to resistance, WHO has encouraged the industry to develop new types of long-lasting insecticidal nets and new insecticides for indoor residual spraying. One of the developments is a new long-lasting insecticidal net that uses piperonyl butoxide (PBO). PBO is a chemical synergist that acts by inhibiting enzymes involved in the natural defense mechanisms of insects, which results in pyrethroid not being detoxified in the insect and the pyrethroid on the long-lasting insecticidal net remaining potent against mosquitoes despite resistance. Such PBO-pyrethroid-treated long-lasting insecticidal nets appear to have similar or better efficacy against resistant mosquitoes under controlled household conditions than standard long-lasting insecticidal nets that do not have PBO. In September, 2015, a WHO expert group reviewed the evidence for PBO long-lasting insecticidal nets to define their deployment. Despite awaiting for more conclusive evidence from community randomised controlled trials (RCTs) with epidemiological outcomes, WHO, nevertheless, has recommended a small rollout in specific situations.

Although the range of insecticide classes suitable for indoor residual spraying use is wider than long-lasting insecticidal nets, few insecticides are effective for more than a few months when sprayed onto walls and this limitation has been a constraint on their adoption and use. The organophosphate pirimiphos-methyl is an exception, and the recently developed long-lasting formulation, Actellic 300CS (Syngenta, Switzerland), is effective for up to 10 months when used for indoor residual spraying. It is now being deployed in several African countries instead of carbamates.

In attempts to accelerate malaria control progress, long-lasting insecticidal nets and indoor residual spraying have been deployed together in several countries. The advantage of combined intervention has, however, been the focus of considerable debate because both observational and RCTs have produced contradictory evidence. In The Gambia and Benin, no difference in malarial outcomes was observed when they were used in combination. On the basis of these data, the effect observed would seem to depend on the insecticide combination used, the vectors present, the coverage and quality of the intervention, and the level and type of insecticide resistance in the vectors.

To develop an improved strategy for control of malaria transmitted by pyrethroid-resistant mosquito vectors, we aimed to compare the effectiveness of PBO long-lasting insecticidal nets with standard long-lasting insecticidal nets as single interventions and in combination with the long-lasting indoor residual spraying of pirimiphos-methyl.

Methods
Study design and participants
We did a cluster RCT of four groups using a two-by-two factorial design. The RCT started on March 1, 2014. The post-intervention assessment period was initially planned for 18 months (from Jan 1, 2015, to June 30, 2016) and was subsequently extended on our request to the funding agency to 24 months (from Jan 1, 2014, to Dec 31, 2016) to enable further assessment of the PBO long-lasting insecticidal net (figure 1).

The study area was Muleba district of the Kagera region in northwest Tanzania, and comprised 40 villages. In 2011, malaria infection prevalence in children was 23%. Anopheles gambiae and Anopheles arabiensis were the only vectors found in 2012. High levels of resistance to pyrethroids have been reported in A gambiae in the study area, and synergy bioassay tests done with PBO and pyrethroid together partially restored the toxicity of pyrethroids. All villages and hamlets with malaria prevalence more than 20% in 2011 were eligible for inclusion in the present trial. Our trial comprised 48 clusters, each divided into an inner core area, which was used for the measurement of study outcomes, and an outer buffer zone of at least 300 m to reduce spill-over effects between clusters. Core and buffer areas of each cluster received the same intervention. All households in the core area with children aged 6 months to 14 years were eligible for malaria cross-sectional survey and mosquito surveillance. We excluded children who were severely ill. Village meetings were held with village leaders, hamlet representatives, community health agents, and villagers to inform them about the trial.

The trial was approved by the ethics review committees of the Kilimanjaro Christian Medical University College, the London School of Hygiene & Tropical Medicine, and the Tanzanian Medical Research Coordinating Committee (NIMR/HQ/R.8s/VolIX/1803). A trial steering committee reviewed progress. Written informed consent from parents or guardians was obtained for each survey and entomology collection.

Randomisation and masking
We used restricted randomisation to allocate the 48 clusters to the four study groups: standard long-lasting insecticidal nets, PBO long-lasting insecticidal nets, standard long-lasting insecticidal nets plus indoor residual spraying, and PBO long-lasting insecticidal nets plus indoor residual spraying. We limited potential imbalance using three restriction variables: malaria infection prevalence in children aged 6 months to 14 years, usage of long-lasting insecticidal nets, and...
socioeconomic status, as recorded in the baseline survey between September and October, 2014. Of the 200 000 random allocations, 29 478 met the restriction criteria of no more than 7% difference in mean malaria prevalence, 10% in mean usage of long-lasting insecticidal nets, and 10% of households in the lowest socioeconomic status tertile between study groups. After verifying that clusters were independently allocated to study groups, we randomly chose one of the eligible allocations.

We masked the inhabitants of each cluster to the type of long-lasting insecticidal nets received. The two types of nets were of similar colour and shape, and only distinguishable by label codes and coloured thread inserted during manufacture. Additionally, we masked field staff, who took blood samples in the cross-sectional surveys, to the study groups the clusters were assigned to. It was not possible to mask either the investigators or the participants to the treatment allocation of indoor residual spraying.

Procedures

We used the following vector control products: Olyset Net (Sumitomo Chemicals, Japan) containing 2% permethrin (standard long-lasting insecticidal net), Olyset Plus (Sumitomo Chemicals, Japan) containing 2% permethrin and 1% PBO (PBO long-lasting insecticidal net), and Actellic 300CS containing microencapsulated pirimiphos-methyl (indoor residual spraying).

We georeferenced all houses in the study using handheld global positioning system units (Legend eTrex, Garmin, USA). The indoor residual spraying campaign was done once only in February, 2015, by the Research Triangle Institute funded by the President’s Malaria Initiative. In the two groups assigned to indoor residual spraying intervention, Actellic 300CS was sprayed to the interior walls and ceilings of each dwelling at the recommended dosage of 1 g/m². The residual decay of Actellic 300CS was monitored by a laboratory technician every 3 months on representative wall surfaces in several houses using WHO Cone bioassay tests (Universiti Sains Malaysia, Malaysia) and a reference strain of susceptible *A gambiae*. The permethrin and PBO contents of the long-lasting insecticidal nets were determined by high-performance liquid chromatography at yearly intervals for 2 years.

Distribution of long-lasting insecticidal nets and health education communication on net usage were done in each cluster by the Tanzania Communication and Development Centre. On the basis of census data, each household received one net per two people. Altogether, 45,000 standard long-lasting insecticidal nets and 45,000 PBO long-lasting insecticidal nets were distributed in February, 2015. Nets already owned were not removed but householders were requested to use the study nets provided.

Cross-sectional household and malaria infection prevalence surveys were done by project field assistants and nurses at baseline in September and October, 2014, and after intervention at the end of each malaria transmission season (June to July and November to December) in 2015 and 2016 (figure 1). During each survey, we randomly sampled 55 households with children aged 6 months to 14 years from the core area of each cluster using the census lists. We then selected up to three eligible children per house at random and recorded information about the number of residents, household assets, house structure, educational status, and use of malaria preventive measures (long-lasting insecticidal nets or other). The minimum target was 80 children per cluster. Enrolled children reported to the clinical team the next day and were tested for malaria using a rapid diagnostic test (CareStart Malaria HRP2/PlDH(pf/PAN) Combo, DiaSys, UK) and for haemoglobin concentration using HemoCue Hb 201+ (HemoCue AB, Sweden). Children diagnosed as malaria positive by the rapid diagnostic test were treated with artemether-lumefantrine according to national guidelines. Any child presenting with illness during the surveys was treated or referred to the nearest health facility if symptoms were severe.

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**Figure 1: Study timetable**

RCT=randomised controlled trial.
Mosquito surveillance was done from March, 2015, to December, 2016, in each cluster by a project field assistant for one night per month in seven randomly selected houses per cluster using CDC Miniature Light Trap Model 512 (John W Hock Company, USA) as a proxy for human biting rates.27 We morphologically identified the collected anophelines to species level21 and tested a subsample for Plasmodium circumsporozoite protein.22 PCR TaqMan assay23 was used to distinguish the two sibling anophelines to species level21 and tested a subsample for Plasmodium falciparum.22

Using wild caught A gambiae and Anopheles funestus of unknown age, the frequency of pyrethroid resistance was determined using 0·75% permethrin papers in WHO cylinder tests. We determined resistance intensity using CDC bottle bioassays and probit analysis to estimate the ratio of the permethrin concentration needed to kill 50% of wild mosquitoes relative to the susceptible strain.

**Outcomes**

The primary outcome was the prevalence of *Plasmodium* spp infection measured by the rapid diagnostic test in children aged 6 months to 14 years assessed by the cross-sectional surveys. The trial was initially funded for 18 months after intervention. Although this period could have been chosen as the endpoint, it was not known for how long the PBO and pyrethroid active ingredients in the long-lasting insecticidal nets would last. This effect needed to be monitored every transmission season. We subsequently secured extension from the funding agency for 24 months. WHO then reset the policy agenda.

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**Figure 2: Trial profile**

| Survey A at 4 months | 12 clusters followed-up | 462 of 660 households included | 1398 children eligible | 1085 children selected | 999 children tested |
|----------------------|-------------------------|-------------------------------|-----------------------|-----------------------|-------------------|
| Survey A at 9 months | 12 clusters followed-up | 429 of 660 households included | 1347 children eligible | 1048 children selected | 933 children tested |
| Survey A at 16 months| 12 clusters followed-up| 470 of 660 households included| 1390 children eligible| 1125 children selected| 1034 children tested|
| Survey A at 21 months| 12 clusters followed-up| 468 of 660 households included| 1404 children eligible| 1131 children selected| 1045 children tested|
| Survey B at 9 months | 12 clusters followed-up| 408 of 660 households included| 1278 children eligible| 983 children selected| 887 children tested |
| Survey B at 16 months| 12 clusters followed-up| 475 of 660 households included| 1440 children eligible| 1150 children selected| 984 children tested |
| Survey B at 21 months| 12 clusters followed-up| 451 of 660 households included| 1429 children eligible| 1118 children selected| 958 children tested |
| Survey C at 9 months | 12 clusters followed-up| 433 of 660 households included| 1250 children eligible| 1012 children selected| 881 children tested |
| Survey C at 16 months| 12 clusters followed-up| 476 of 660 households included| 1451 children eligible| 1113 children selected| 984 children tested |
| Survey C at 21 months| 12 clusters followed-up| 453 of 660 households included| 1429 children eligible| 1118 children selected| 958 children tested |
| Survey D at 9 months | 12 clusters followed-up| 430 of 660 households included| 1250 children eligible| 1012 children selected| 881 children tested |
| Survey D at 16 months| 12 clusters followed-up| 465 of 660 households included| 1401 children eligible| 1130 children selected| 972 children tested |
| Survey D at 21 months| 12 clusters followed-up| 468 of 660 households included| 1404 children eligible| 1131 children selected| 1045 children tested|

48 clusters assessed for eligibility
48 randomly allocated to intervention
Table 1: Baseline characteristics

| Study cluster characteristics | Standard LLIN | PBO LLIN | Standard LLIN plus IRS | PBO LLIN plus IRS |
|-------------------------------|--------------|----------|------------------------|------------------|
| Total population in core and buffer areas | 33,820 | 32,861 | 38,081 | 31,138 |
| Population in core area | 15,947 | 16,282 | 16,358 | 14,845 |

Household characteristics

| Study cluster characteristics | Standard LLIN | PBO LLIN | Standard LLIN plus IRS | PBO LLIN plus IRS |
|-------------------------------|--------------|----------|------------------------|------------------|
| Median altitude of the households selected (range; N) | 1310 (1138-1654; 465) | 1275 (1138-1563; 500) | 1298 (1129-1486; 508) | 1318 (1152-1543; 510) |
| Households in the lowest socioeconomic category | 146/464 (31%) | 166/534 (31%) | 198/528 (38%) | 163/467 (35%) |
| Households with adequate long-lasting insecticidal nets | 174/545 (32%) | 223/582 (38%) | 230/580 (40%) | 211/561 (38%) |
| Households with ≥1 long-lasting insecticidal nets | 356/545 (65%) | 410/582 (70%) | 402/581 (69%) | 378/561 (67%) |
| Long-lasting insecticidal nets use in all age groups | 902/2996 (30%) | 810/3078 (26%) | 882/3197 (28%) | 810/3078 (26%) |

Median age, years (IQR; N)

| Study cluster characteristics | Standard LLIN | PBO LLIN | Standard LLIN plus IRS | PBO LLIN plus IRS |
|-------------------------------|--------------|----------|------------------------|------------------|
| Median age, years (IQR; N) | 6 (3-10; 885) | 6 (3-10; 991) | 6 (3-10; 1017) | 6 (3-10; 967) |
| Long-lasting insecticidal net use in selected children | 348/891 (39%) | 315/992 (32%) | 315/1018 (31%) | 307/970 (32%) |
| Malaria infection prevalence | 600/885 (68%) | 606/991 (61%) | 678/1018 (67%) | 615/967 (64%) |
| Anaemia prevalence in children <5 years* | 36/328 (11%) | 36/378 (10%) | 34/372 (9%) | 32/362 (8%) |
| Mean number of vectors found indoors per house per night (95% CI; N) | 17.0 (0-34.7; 129) | 37.0 (4-70.1; 119) | 11.8 (0-24.7; 117) | 43.6 (9.7-77.6; 129) |
| Sporozoite rate | 32/809 (5%) | 59/1085 (5%) | 37/733 (5%) | 35/1161 (3%) |

Data are n/N (%), unless stated otherwise. Data for household, children, and entomological characteristics are only for the core area. LLIN=long-lasting insecticidal net. PBO=piperonyl butoxide. IRS=indoor residual spraying.

Statistical analysis was done using Stata (version 12). All statistical inferences allowed for within-cluster correlation of responses by use of a robust variance estimator to calculate SEs. No allowance was made for multiplicity of testing in the analyses. In the intention-to-treat analysis, logistic regression was used to estimate odds ratios (ORs) of the effect of each of the two interventions (PBO long-lasting insecticidal nets vs standard long-lasting insecticidal nets, and indoor residual spraying vs no indoor residual spraying) on prevalence of infection and prevalence of anaemia. We estimated interaction between the two main effects by including an appropriate term in the model. We also examined the effect of each intervention (PBO long-lasting insecticidal nets, combination of standard long-lasting insecticidal nets plus indoor residual spraying, and combination of PBO long-lasting insecticidal nets plus indoor residual spraying) compared with the control group (standard long-lasting insecticidal net). Effects were interpreted in relation to a postulated minimum difference of 28% for factorial analysis and 40% for the analysis of each intervention. Analysis of anaemia was restricted to children aged 6 months to 4 years. The per-protocol analysis is available in the appendix.

Vector density and entomological inoculation rate were analysed with negative binomial regression, after adjusting for baseline. Statistical analysis was done using negative binomial regression, after adjusting for baseline. Entomological inoculation rate was estimated as the mean number of sporozoite-infected Anopheles per house per night and weighted to account for the proportion of collected Anopheles processed for sporozoites. The proportion of sporozoite-infected mosquitoes (the sporozoite rate) was compared using logistic regression.

See Online for appendix.
This trial is registered with ClinicalTrials.gov, number NCT02288637.

**Role of the funding source**  
The funder of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

**Results**  
The study area comprised 29,365 households and a population of 135,900. Of the 10,560 households selected for post-intervention survey, 7,184 (68.0%) were included whereas 1127 (10.7%) were ineligible (no children younger than 15 years), 150 (1.4%) refused, 1543 (14.6%) were absent, and 556 (5.3%) were unvisited. Of the 17,377 eligible children selected, 15,492 (89.2%) attended for testing (figure 2). Pre-intervention household and demographic characteristics, as well as coverage and usage of long-lasting insecticidal nets were similar between study groups (table 1). Malaria infection prevalence was reported in 2499 (65%) of 3861 children at baseline, and any difference between groups was within the tolerances set for the constrained randomisation. The average indoor Anopheles density was 27.6 per house per night and the proportion of mosquitoes with sporozoites was 4.5%.

Of the 13,689 Anopheline mosquitoes collected, 11,106 (85.7%) were A gambiae sensu lato and 510 (3.7%) were A funestus. Of the 990 A gambiae sensu lato identified to species, 946 (95.6%) were A gambiae sensu stricto and 44 (4.4%) were A arabiensis.

Between baseline and the first cross-sectional survey 4 months after intervention, long-lasting insecticidal net ownership (one net per household) increased to 1690 (97.6%) of 1732 households, access (household with enough long-lasting insecticidal net per sleeping place) increased to 1550 (89.6%) of 1730, and long-lasting insecticidal net use increased to 7807 (76.9%) of 10,152 (appendix). Long-lasting insecticidal net usage was similar between groups and between surveys during the first year. In the second year, 21 months after intervention, 2027 (94%) of 2187 households selected for the survey received indoor residual spraying in the two groups assigned to this intervention. The insecticide residues on sprayed walls decayed gradually over the year; mosquito mortality in WHO cone bioassays was 99% (566 of 570 exposed mosquitoes died, 95% CI 97.9–100) shortly after spraying, 82% (356 of 432, 75.4–89.5) after 9 months, and 57% (495 of 840, 51.4–66.4) after 12 months.

In the intention-to-treat factorial analysis for the prevalence of malaria infection, the effect of indoor residual spraying versus no indoor residual spraying was evident at 4 months (OR 0.50, 95% CI 0.31–0.82; p=0.0071) whereas there was no evidence of a difference between PBO long-lasting insecticidal nets and standard LLIN plus IRS at 4 months (OR 1.37, 95% CI 0.66–2.86).

827 (94%) of 878 households selected for the survey received indoor residual spraying in the two groups assigned to this intervention. The insecticide residues on sprayed walls decayed gradually over the year; mosquito mortality in WHO cone bioassays was 99% (566 of 570 exposed mosquitoes died, 95% CI 97.9–100) shortly after spraying, 82% (356 of 432, 75.4–89.5) after 9 months, and 57% (495 of 840, 51.4–66.4) after 12 months.

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The mortality of mosquitoes exposed to permethrin for resistance determination in the WHO cylinder tests was significantly lower in the indoor residual spraying groups compared to the non-IRS groups. In the second year, the mortality of mosquitoes exposed to permethrin for resistance determination in the WHO cylinder tests was significantly lower in the indoor residual spraying groups than in the non-IRS groups. In the analysis of the individual group comparisons, the difference in malaria infection prevalence between the reference group (standard long-lasting insecticidal net) and the PBO long-lasting insecticidal net group or the combination of the standard net plus indoor residual spraying group was greater than that observed in the factorial analysis at every timepoint between PBO nets and non-PBO nets or between indoor residual spraying and no indoor spraying (table 2). The individual group comparison also provides information about the effect of the PBO long-lasting insecticidal net plus indoor residual spraying intervention.

Prevalence of severe-to-moderate anaemia was lower for the groups receiving PBO long-lasting insecticidal net compared with their standard long-lasting insecticidal net reference groups, and was also lower in the groups receiving indoor residual spraying than in the non-indoor residual spraying reference groups in the surveys after 9 months and 16 months intervention (table 3). Results of the per-protocol analyses of malaria infection and anaemia were similar to that of the intention-to-treat analyses (appendix).

A total of 16,371 vector mosquitoes were collected in 5756 indoor light-trap collections over the 2 years. In the first year, vector densities, sporozoite rates, and entomological inoculation rates were lower in the PBO long-lasting insecticidal net groups than in the standard long-lasting insecticidal net groups (table 4), but only entomological inoculation rate was significantly lower in the indoor residual spraying groups than in the non-indoor residual spraying groups. In the second year, the entomological inoculation rate in the PBO long-lasting insecticidal net groups remained lower than in the standard long-lasting insecticidal net groups but the effect of indoor residual spraying on entomological inoculation rate had largely diminished by this time compared with the entomological inoculation rates of 2015.
Discussion

This trial showed that long-lasting insecticidal nets incorporating the synergist PBO (Olyset Plus) were more effective than the standard pyrethroid long-lasting insecticidal net (Olyset Net) in reducing malaria infection prevalence in an area of high usage of these nets and high pyrethroid resistance in the primary vectors. The additional effect of the PBO long-lasting insecticidal nets on malaria prevalence was evident at the end of the first year with a 44% protective efficacy and at the end of the second year with a 33% protective efficacy compared with the standard long-lasting insecticidal nets. These findings were supported by the entomological outcomes, which showed a significant reduction in malaria transmission, with entomological inoculation rates being reduced by 87% during the first year and 67% during the second year in areas receiving PBO long-lasting insecticidal nets compared with standard long-lasting insecticidal nets. At 9 months, the addition of pririmiphos-methyl indoor residual spraying to the standard long-lasting insecticidal nets provided similar protection against malaria (44% protective efficacy) relative to the standard nets alone, whereas the addition of indoor residual spraying to PBO long-lasting insecticidal nets did not significantly improve protection based on the interaction observed when both indoor spraying and PBO long-lasting insecticidal nets effect were at their strongest. The impact of indoor residual spraying on the entomological inoculation rates was more than 95% in the first year. This effect on malaria transmission occurred shortly after implementation of indoor residual spraying whereas the effect of PBO long-lasting insecticidal nets took longer. This rapid impact of indoor residual spraying is one reason why this intervention is sometimes more favoured than long-lasting insecticidal net distribution during malaria epidemics, although there has been a paucity of evidence to justify this advice.12 Our cluster RCT would support this recommendation, provided high indoor residual spraying coverage can be quickly achieved. Residual insecticidal activity of pirimiphos-methyl on the sprayed walls was observed up to 12 months after a single round of spraying. Following the decay in residual activity during the second year when no spraying was done, the effect of indoor residual spraying on entomological inoculation rates diminished and malaria prevalence increased but not to the level observed in the standard long-lasting insecticidal net control group, which had not received indoor residual spraying in year 1. A sustained effect on malaria transmission would require recurrent annual campaigns of indoor residual spraying.

This trial is the first to provide evidence to suggest that incorporation of the synergist PBO to long-lasting insecticidal nets provides improved community protection compared with standard pyrethroid-only nets against malaria transmission by pyrethroid-resistant vector populations. Previous small-scale experimental hut studies of PBO long-lasting insecticidal nets measured entomological outcomes such as mosquito mortality and biting rates. In Benin, these studies showed that Olyset Plus was more effective than standard Olyset Net against pyrethroid-resistant *A gambiae*, both before and after multiple washing of the nets.13 In Tanzania where *A gambiae* was still susceptible to pyrethroids, the differential effect between Olyset Plus and standard Olyset Net was less evident.13 Parallel studies with a different type of PBO long-lasting insecticidal net (PermaNet 3.0) showed improved outcomes with the
Table 4: Entomological outcomes by intervention (PBO LLIN vs no PBO LLIN, and IRS vs no IRS) in 2015 and 2016

| Year: 2015 | Vector density per night per household | Sporozoite rate | EIR per month per household* |
|-----------|--------------------------------------|----------------|------------------------------|
|           | N  | Mean (SD) | DR (95% CI) | p value | n/N (%) | OR (95% CI) | p value | N  | Mean (SD) | DR (95% CI) | p value |
| No PBO LLIN | 896 | 2.61 (8.97) | 1 (ref) | - | 20.952 (2%) | 1 (ref) | - | 862 | 0.90 (5.42) | 1 (ref) | - |
| PBO LLIN | 961 | 1.85 (7.12) | 0.33 (0.16-0.69) | 0.0038 | 2.648 (1<%) | 0.25 (0.07-0.88) | 0.0317 | 911 | 0.13 (3.07) | 0.13 (0.03-0.53) | 0.0055 |
| No IRS | 939 | 2.34 (8.18) | 1 (ref) | - | 21.988 (2%) | 1 (ref) | - | 901 | 1.01 (5.85) | 1 (ref) | - |
| IRS¶ | 918 | 2.09 (7.96) | 0.63 (0.27-1.43) | 0.2652 | 1.612 (1<%) | 0.15 (0.02-1.02) | 0.0519 | 872 | 0.25 (0.89) | 0.03 (0.00-0.24) | 0.0014 |

Interaction coefficient
- - 1.35 (0.44-4.18) 0.5940 - NA NA - - NA NA

Year: 2016

| No PBO LLIN | 1946 | 3.60 (16.86) | 1 (ref) | - | 80.22/6 (4%) | 1 (ref) | - | 1793 | 1.15 (6.53) | 1 (ref) | - |
| PBO LLIN | 1953 | 2.68 (11.33) | 0.40 (0.20-0.80) | 0.0101 | 27.19/31 (1%) | 0.38 (0.15-0.92) | 0.0311 | 1845 | 0.39 (3.91) | 0.13 (0.03-0.81) | 0.0189 |
| No IRS | 1942 | 2.92 (9.34) | 1 (ref) | - | 64.22/07 (3%) | 1 (ref) | - | 1801 | 1.00 (6.04) | 1 (ref) | - |
| IRS¶ | 1957 | 3.46 (18.01) | 0.93 (0.47-1.85) | 0.8390 | 43.19/60 (2%) | 0.81 (0.37-1.78) | 0.0580 | 1837 | 0.58 (4.87) | 0.48 (0.25-0.94) | 0.0340 |

Interaction coefficient
- - 1.00 (0.36-2.75) 0.9970 - 1.13 (0.35-3.63) 0.8308 - - 1.38 (0.47-4.08) 0.5532

DR for vector density and EIR and OR for sporozoite rates are adjusted for their respective baseline value. EIR=entomological inoculation rate. DR=density ratio. OR=odds ratio. LLIN=long-lasting insecticidal net. PBO=piperonyl butoxide. IRS=indoor residual spraying. NA=not applicable. 1 The mean and DR of the EIR are weighted to account for the proportion of mosquitoes sampled to be tested for sporozoites. Interaction not estimated in year 1 for sporozoite and EIR outcomes, because sporozoite rate was null in the PBO LLIN plus IRS group. ‡PBO LLIN and PBO LLIN plus PBO. ¶Standard LLIN and standard LLIN plus IRS. ⊳PBO LLIN and PBO LLIN plus IRS. §Standard LLIN and PBO LLIN. ¶¶Standard LLIN plus IRS and IRS plus IRS.

Despite the 83% loss in PBO content after 21 months, the PBO and permethrin retained on the net remained highly effective against malaria infection and entomological inoculation rates throughout. By contrast, the loss of residual activity of the single round of indoor residual spraying of Actellic 300CS led to resumption of transmission and to increasing entomological inoculation rates and malaria prevalence in the second year. The PBO nets will be monitored during a third year to assess whether effectiveness is maintained at low PBO content. There was also a 42% loss of permethrin content in Olyset Plus and 22% in Olyset Net over the two years. The differential release rate of permethrin in the two nets has been observed in other studies, and it has been suggested in an earlier WHO review of Olyset Plus that the more effective performance of the PBO net is due to the higher release rate and surface concentration of permethrin in this net compared with Olyset Net. Although this argument cannot be completely refuted by our data, the A gambiae and A funestus vectors in the Muleba area are highly resistant to pyrethroid and any difference in surface permethrin between Olyset Plus and Olyset Net in our trial is unlikely to result in differential mortality rate. A study has shown that under household conditions a 20-times increase in the surface content of permethrin on hand-treated nets causes no increase in mortality to free-flying pyrethroid-resistant A gambiae. Furthermore, synergy tests with PBO showed that pyrethroid-resistant A gambiae from our study area are killed by a permethrin concentration they would normally survive if it were not mixed with PBO. The more effective performance of PBO long-lasting insecticidal nets compared with standard long-lasting insecticidal nets in reducing the prevalence of malaria infection, together with no change in prevalence following the initial distribution and high usage of standard nets, suggests that insecticide resistance of the magnitude reported is compromising the effectiveness of standard pyrethroid nets in northwest Tanzania. A recent study in neighbouring Uganda reported no change in incidence of malaria before and after the distribution of standard long-lasting insecticidal nets. Other studies have reported the failure of these nets to reduce entomological indicators after the standard long-lasting insecticidal nets developed holes. From our study design, it is not clear whether the standard nets still provide some degree of protection. Although a previous study in Muleba done in 2012 showed that users of standard long-lasting insecticidal nets were slightly better protected (OR 0.83) against malaria infection prevalence than non-users of nets, this finding should be contrasted with the much larger effect of PBO long-lasting insecticidal nets versus standard nets (OR 0.37) in the present study. In areas with more moderate levels of pyrethroid resistance, standard nets still
provide personal protection. A study in Malawi, for example, showed that standard nets reduced malaria incidence by 30% in children in an area where pyrethroid-resistant *A. funestus* was the main vector. In Kenya, the use of standard nets provided 45% protection against the incidence of malaria infection as compared with those not using long-lasting insecticidal nets, but incidence still remained high in net users. The strength or intensity of resistance in the local primary vector species might be the factor defining the level of protection to be derived from standard long-lasting insecticidal nets.

Our study provides further insight into the question of whether indoor residual spraying and long-lasting insecticidal nets should be combined to accelerate the control of malaria. In a previous cluster RCT in Muleba, where conditions of high pyrethroid resistance and moderate usage of long-lasting insecticidal nets (50%), indoor residual spraying with the carbamate bendiocarb provided an added benefit (OR 0·43). In the present study, a single round of indoor residual spraying with the long-lasting pirimiphos-methyl capsule suspension in combination with standard nets was sufficient to give long-term additional protection over two transmission seasons (OR 0·33), whereas the bendiocarb required two rounds to achieve an effect of similar size, owing to its shorter residual activity on walls.

The combination of indoor residual spraying of pirimiphos-methyl and PBO long-last insecticidal nets have been suggested to be antagonistic. This concern arose because pirimiphos-methyl requires oxidation by cytochrome P450 enzymes within the mosquito before it becomes toxic. Uptake of PBO from previous contact with Olyset Plus nets might potentially inhibit this activation process. Although the present cluster RCT neither confirmed nor disproved any antagonistic effect, it showed there was limited benefit to be gained from adding this indoor residual spraying product to PBO nets. Whether another indoor residual spraying insecticide, which does not require activation by cytochrome P450s, would prove an effective partner to PBO long-lasting insecticidal nets is not known. The present cluster RCT also implies that where indoor spraying with pirimiphos-methyl is being applied annually, the substitution of PBO nets for standard nets would provide little or no additional benefit. Considering the focal coverage of indoor residual spraying compared with the much wider coverage of long-lasting insecticidal nets in Africa, an important question from a public health standpoint is which strategy should be adopted in areas where standard long-lasting insecticidal nets might be losing effectiveness because of high intensity of pyrethroid resistance in the local vector? The substitution of PBO long-lasting insecticidal nets in such areas would provide a substantial benefit, similar to that which annual indoor residual spraying campaigns might provide.

This trial has several potential limitations. Buffer areas of 300 m were small compared with what has been used in other trials, which might not have totally prevented contamination. However, any spill-over would have lessened rather than increased the effect size between intervention groups. Additionally, the community was not masked to the indoor residual spraying allocation, which might have led to reduced child attendance at clinic sessions. However, such bias has not been observed and attendance was similar across all intervention groups. Furthermore, we used vector density in CDC light trap collections as a proxy to estimate entomological inoculation rate, rather than vector biting rate in human landing catches. The light trap approach is becoming more common in trials for pragmatic and ethical reasons; and although it could have led to error in the estimation of transmission intensity, it would not have affected the relative difference in entomological inoculation rates observed between the study groups. Finally, our trial was not powered to detect interactions.

In conclusion, this trial shows the residual efficacy of indoor residual spraying with pirimiphos-methyl for malaria control of over 1 year, and provides strong evidence for increasing the coverage of PBO long-lasting insecticidal nets over standard long-lasting insecticidal nets of pyrethroid to meet the increasing challenge of pyrethroid resistance and to improve personal and community protection from malaria, particularly in areas of intense pyrethroid resistance. As a consequence of the trial, WHO has made this policy recommendation.

**Contributors**

NP, IK, and MR conceived and designed the study. CDM, FWM, and WK advised on interventions, study communities, and coordination with local and national authorities. NP, JFM, EL, JDC, AW, and AM implemented the study. NP and JFM analysed the data. NP, JFM, IK, and MR interpreted the data. NP and JFM wrote the first draft of the manuscript. IK and MR critically revised the manuscript for important content. MR led the coordination with international policy authorities. EL, JDC, AW, CDM, AM, FWM, and WK revised the manuscript.

All authors read and approved the final version of the manuscript.

**Declaration of interests**

We declare no competing interests.

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