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EVALUATION AND COMPARISON OF SPRAY EQUIPMENT FOR INDOOR RESIDUAL SPRAYING

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ABSTRACT. The World Health Organization (WHO) has recently recommended indoor residual spraying (IRS) as part of a vector control strategy to combat *Aedes*-borne diseases, including dengue, chikungunya, and Zika viruses. Hand compression sprayers have been used in malaria prevention and control programs worldwide since the 1950s and are a standard for IRS application. However, there are technological advances that should be considered to improve IRS application (e.g., flow-control valves, rechargeable-battery equipment, reduced-drift nozzles, etc.), particularly if interventions are performed in urban areas to target *Aedes aegypti*. Using WHO guidelines, we contrasted technical characteristics of potential IRS equipment including hand compression sprayers (Hudson X-pert, Goizper IK Vector Control Super), rechargeable-battery sprayers (Solo 416, Birchmeier REC 15ABZ, Hudson NeverPump), and motorized sprayers (Honda WJR 2525, Kawashima AK35GX). Measurements included flow rate, droplet size, battery/fuel life, and technical/physical characteristics. Flow rate, the most important parameter, of the Hudson X-pert was stabilized at 550 ml/min by the use of a control flow valve (CFV). The IK Vector Control Super had integrated CFVs and produced a similar flow as the Hudson X-pert. Rechargeable-battery equipment provided consistent flow as well as negligible noise. Motorized sprayers also produced consistent flow, but their weight, high noise pollution when used indoors, and high engine temperature made them highly unpleasant for technicians. We identify alternatives to the more traditional hand compression Hudson X-pert sprayer with technical and operational considerations for performing IRS.

KEY WORDS *Aedes aegypti,* hand compression pump, insecticide, spray equipment

INTRODUCTION

Indoor residual spraying (IRS) is the application of long-lasting residual insecticides to the walls, eaves, and ceilings of houses or structures, targeting vectors that land or rest on these surfaces (WHO 2006, 2007, 2015). Although widely used in malaria, Chagas disease, and leishmaniasis control (WHO 2006, 2007, 2010), IRS implementation in control of urban *Aedes aegypti* (L.) has suffered from limited evidence of its efficacy (Bowman et al. 2016, Vazquez-Prokopec et al. 2017a) and the challenge of scaling up interventions within large city environments (Paredes-Esquivel et al. 2016, Samuel et al 2017, Hladish et al. 2018, Paz-Soldán et al. 2018). Recent evidence from Cairns, Australia, indicates that IRS targeting *Ae. aegypti* indoor resting sites (TIRS) such as under beds/furniture and on lower walls can lead to an 86–96% reduction of dengue cases (Vazquez-Prokopec et al. 2017b, Dunbar et al. 2019). The TIRS exploits *Ae. aegypti* resting behavior, which occurs predominantly indoors and below 1.5 m (Dzul-Manzanilla et al. 2017). During the Zika public health emergency, the World Health Organization (WHO) Vector Control Advisory Group recommended the adoption of TIRS as part of a vector control strategy to combat *Aedes*-borne diseases, including dengue, chikungunya, and Zika viruses (WHO 2016). Furthermore, a stochastic simulation model predicted very high TIRS impact in preventing dengue when interventions were performed preventively (i.e., prior to the regular transmission season) and with high coverage (Hladish et al. 2018). One approach to increasing TIRS coverage is to improve the efficiency of interventions, or the time and resources it takes to spray per house. While spraying only resting sites significantly reduces TIRS spraying time compared to "classic" malaria-targeted IRS, improvements in equipment design and technical characteristics can further improve intervention quality and efficiency (Knapp et al. 2015).

Hand compression sprayers such as the Hudson X-pert (H. D. Hudson Manufacturing Company, Chicago, IL) were designed at the beginning of the malaria eradication campaigns of the 1940s–1950s, and are considered the gold standard for IRS application. Recent technological advances in spray equipment have led to alternative hand compression equipment currently in use as part of scaled-up malaria IRS campaigns (e.g., plastic tank sprayers with integrated flow-control valves; IK Vector Control Super, Goizper Spraying, New Bedford, MA). While the Hudson X-pert and the IK Vector Control Super sprayers have similar technical properties, they still depend on technicians to

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Table 1. List of 3 types of indoor residual spray equipment evaluated.

Equipment type/model	Company
Hand compression	
Hudson X-pert Model 93793	H. D. Hudson, Chicago, IL
IK Vector Control Super	Goizper Group, Antzuola, Spain
Rechargeable battery	
Solo 416	Solo, Sindelfingen, Germany
REC 15ABZ	Birchmeirer, Stetten, Switzerland
Hudson NeverPump	H. D. Hudson, Chicago, IL
Motorized	
Honda WJR 2525	Honda, Jakarta, Indonesia
Kawashima Spray AK35GX	Honda, Jakarta, Indonesia

manually pump in order to pressurize the tanks before spraying. In the urban context, efficient TIRS implementation requires expeditious interventions inside homes. Newer IRS equipment, including rechargeable-battery or motorized equipment, may overcome issues associated with hand compression sprayers and therefore can help increase the efficiency of TIRS application.

Recent WHO guidelines for IRS equipment outline technical specifications to help select acceptable hand compression equipment (WHO 2018). Given the lack of comparative evaluations of existing IRS spray equipment, we used WHO guidelines (WHO 2018) to contrast technical characteristics of existing equipment, which included hand compression, rechargeable-battery, and motorized sprayers. The objective of this study was to identify and compare alternative IRS equipment by evaluating potential sprayers based on flow rate, droplet size, battery or fuel life, and technical/physical characteristics.

MATERIALS AND METHODS

We first conducted an online exploration of existing sprayers currently in use in public health or agriculture for residual insecticide applications. From a total of 10 sprayers, we selected those meeting the WHO criteria for weight, dimension of opening, and presence of pressure relief valve (WHO 2018). Six sprayers were selected (in addition to the Hudson X-pert) and grouped into 3 categories; 1) hand compression sprayers ($n = 2$), 2) rechargeable-battery sprayers ($n = 3$), and 3) motorized sprayers ($n = 2$) (Table 1).

Following WHO procedures (WHO 2007, 2010, 2015), we evaluated sprayers based on 4 major categories; 1) flow rate, 2) droplet size (Gunning et al. 2018), 3) battery and fuel life, and 4) technical/physical characteristics (Table 2), including equipment maintenance. Technical data pertaining to physical characteristics (e.g., sprayer material, weight, dimensions, etc.) were obtained from product manuals or company websites and were evaluated at the Unidad Colaborativa de Bioensayos Entomologicos from the Autonomous University of Yucatan, a reference center for equipment and insecticide evaluations in Mexico.

Flow rate was measured as the amount of liquid expelled into a graduated cylinder per minute (WHO 2007, 2010, 2015). For the hand compression equipment, tanks were filled completely with water and pressurized as recommended by the corresponding product manual. Rechargeable-battery and motorized equipment tanks were similarly filled completely with water. Once a tank was filled, for each equipment, flow rate was measured by the amount of water expelled into a graduated cylinder over the course of a minute. Flow rate was measured 5 times per tank, at which point tanks were refilled and the measurements were repeated 2 more times. Red control flow valves (CFV; 1.5 bar output pressure; model CFV.R11/16SYV.ST; CFValue, Gate LLC, Sebastian, FL) and 8002EVS nozzles (Teejet® Technologies, Spraying Systems Co., Glendal Heights, IL) were used with all evaluated equipment during flow rate measurements, with the exception of the IK Vector Control Super, which uses a yellow CFV (1.0 bar output pressure, model CFV.Y11/16SYV.ST; CFValue, Gate).

For rechargeable-battery and motorized equipment, the volume of water (liter) and number of tanks that could be applied by a single battery charge or full fuel tank, as well the time until the battery depleted or fuel tank emptied (minutes), were measured 3 times each. For rechargeable-battery equipment, time required to recharge the battery was also measured. Battery and fuel life measurements were repeated 3 times for each sprayer. Additionally, for rechargeable-battery and motorized equipment, the quantity of sound was measured 3 times using a decibel meter (digital decibel meter, model Her-403; Steren, Mexico City, Mexico).

For all sprayers, sprayer tanks were filled with water and droplet size was measured using a droplet measuring system (Droplet Counter IV; KLD Labs Inc., Huntington Station, NY). During each measurement, the droplet measuring system was positioned 45 cm away from the sprayer nozzle (i.e., simulating the distance recommended between the spray nozzle and the surface). Droplet size was measured 5 times for each sprayer, each replicate collecting between 100 and 500 droplets, and the median mass diameter (equivalent to the [$D_{V0.5}$]) was recorded. Following each measurement, the measurement probe was washed with a 50:50 solution of acetone and xylene.

RESULTS

Using CFVs (either integrated within the equipment, or added to the sprayer's nozzle) led all tested

Table 2. Technical and physical characteristics measured for potential indoor residual spray equipment as specified by WHO (2018) guidelines.

	Hand compression		Rechargeable battery			Motorized	
Technical data	Hudson X-pert	IK Vector Control	REC 15ABZ	Solo 416	NeverPump	Honda WJR 2525	Kawashima Spray AK35GX
Material	Metal	Plastic	Plastic	Plastic	Plastic	Plastic	Plastic
Corrosion resistant (true/false)	True	True	True	True	True	True	True
Ultra violet resistant (true/false)	True	True	True	True	True	True	True
Pressure resistant (true/false)	True	True	True	True	True	True	True
Weight (kg)	5.1	3.0	4.4	5.2	7.4	12.0	9.0
Capacity (liters)	10	10	15	20	15	25	25
Total weight (kg)	15.1	13.0	19.4	25.2	22.4	37.0	34.0
Capacity max level mark (true/false)	True	True	True	True	True	True	True
Capacity 1-liter mark (true/false)	False	True	True	True	True	False	True
Opening filter dimension (mm)	95	93	123	135	120	160	145
Filter filler openings (true/false)	False	True	True	True	True	True	True
Pump performance (true/false)	n/a	n/a	True	True	True	True	True
Liquid filter lines (true/false)	True	True	True	True	False	True	True
No. of filters	2	2	2	1	2	1	1
Lance length (mm)	500	580	530	567	520	540	740
Lance bend (true/false)	False	True	True	True	True	False	False
Lance extendible (true/false)	False	False	False	True	False	False	False
Flow rate control device (true/false)	True	True	True	True	True	True	True
Flow rate (true/false)	True	True	True	True	True	True	True
No. of straps	1	2	2	3	2	2	2
Strap width (mm)	50	50	70	70	65	100	70
Strap length (mm)	100	103	99	94	120	100	91
Adjustable strap (true/false)	True	True	True	True	True	True	True

equipment except the IK Vector Control Super to produce an output flow rate within the expectation of 550 ± 5% ml/min, and a droplet size between 120 and 200 μm, within the range acceptable for IRS (WHO 2018) (Table 3). Rechargeable-battery and motorized sprayers produced very consistent flow rates, with 4 out of 5 standard errors among replicates below 0.7 ml/min (Table 3). No sprayer showed errors to be at or higher than 5%, the level of tolerance set by WHO (WHO 2018).

Full charge on the batteries of rechargeable-battery sprayers lasted for 175–288 liters of spray and 323–589 min of continuous operation (Table 4). The REC 15ABZ, while being the rechargeable-battery sprayer with the lowest battery life, was also the most consistent across replicates (Table 4). Full tanks of motorized sprayers lasted for 62–77 liters and 108–156 min of continuous operation (Table 4). The average recharge time for REC 15ABZ battery was 72.3 ± 3.9 min (mean ± SEM) and was the fastest of the 3 rechargeable battery sprayers. The recharge time for the Hudson NeverPump and the Solo 416 batteries were considerably longer, averaging 354.7 ± 36.1 min and 329.0 ± 18.8 min, respectively.

With the exception of the Hudson X-pert, all other sprayers were built primarily with plastic materials (Table 2). Weight is an important operational factor and was lowest for the IK Vector Control Super, whereas all rechargeable-battery sprayers had weights similar to the Hudson X-pert. Given differences in tank capacity, weight of sprayers with full tanks varied from 15 kg for the Hudson X-pert to

Table 3. Flow rate and droplet size of 3 types of potential indoor residual spraying equipment.

Equipment type/model	Flow rate (ml/min)[1]	Droplet size (μm)[1]
Hand compression		
Hudson X-pert	561.7 ± 1.1	152.6 ± 24.2
IK Vector Control Super	589.9 ± 3.3	196.1 ± 19.7
Rechargeable battery		
Solo 416	550.2 ± 0.4	161.5 ± 21.6
REC 15ABZ	549.9 ± 0.3	170.9 ± 27.1
Hudson NeverPump	557.1 ± 0.7	156.2 ± 12.6
Motorized		
Honda WJR 2525	550.0 ± 0.0	136.8 ± 9.2
Kawashima Spray AK35GX	534.0 ± 1.0	146.1 ± 22.8

[1] Mean ± SEM, based on 5 replicates.

Table 4. Battery life, fuel life, and sound pressure/noise (decibels) of potential indoor residual spray equipment.

Equipment type/model	No. of tanks[1]	No. of liters[1]	Minutes[1]	Decibels[2]
Rechargeable battery				
Solo 416	14 (13–16)	281 (260–323)	411 (367–461)	76.1 ± 0.03
REC 15ABZ	11 (11)	175 (168–178)	323 (305–339)	78.6 ± 0.06
Hudson NeverPump	19 (14–23)	288 (219–345)	589 (470–600)	74.3 ± 0.02
Motorized				
Honda WJR 2525	3 (2–3)	77 (60–86)	156 (130–183)	96.5 ± 0.05
Kawashima Spray AK35GX	2 (2)	62 (59–65)	108 (101–115)	109.4 ± 0.12

[1] Total number (range). Values measured are based on 3 replicates.
[2] Mean ± SEM, based on 3 replicates.

37 kg for the Honda WJR 2525 (Table 2). When tanks were filled, both motorized sprayers exceeded the 25-kg maximum weight specified by the WHO guidelines. While motorized sprayers had large tank capacities, their excessive weight may hinder their use as part of operational vector control programs. Other physical attributes of sprayers showed very similar materials and parameters across the tested equipment (Table 2). All rechargeable-battery sprayers had sound levels below 85 decibels (dB) (Table 4), indicating they are safe to use without any ear protection, based on WHO recommendations (WHO 2018). Conversely, both motorized sprayers exceeded 85 dB (Table 4) and required ear protection by the operators while in use. Equipment maintenance was minimal for hand compression (e.g., changing of nozzles and rubber gaskets) and rechargeable-battery sprayers (e.g., changing of nozzles and rubber gaskets, battery upkeep). Maintenance of motorized sprayers ranged from minimal tasks (e.g., changing spark plugs) to major tasks (e.g., changing air filters, carburetor, etc.).

DISCUSSION

We identified alternatives to the Hudson X-pert with technical and operational improvements for performing IRS in urban areas. Our evaluation shows that there are many options for urban IRS that include an array of sprayers with important advantages for intervention scale-up. While our evaluation was stimulated by the need to find alternative spray equipment for urban IRS targeting *Aedes*-borne diseases, we believe that our findings could similarly inform malaria-targeted IRS (Knapp et al. 2015).

Motorized equipment is currently being used for indoor spraying (Stoddard et al. 2014, Samuel et al. 2017, Gunning et al. 2018), whereby insecticide applied at ultra-low volume (ULV) with portable equipment is implemented indoors as a rapid approach to contain an outbreak. Such methods provide a rapid, albeit transient, impact on indoor populations of adult mosquitoes (Stoddard et al. 2014, Samuel et al. 2017). We show that similar motorized equipment can deliver the appropriate droplet size required for TIRS, provided they are fitted with CFVs. While motorized sprayers may help transition indoor ULV spraying to TIRS, they are also associated with important constraints. Compared to hand compression sprayers and rechargeable-battery sprayers, motorized sprayers were heavier, bulkier, louder, and more expensive. Such factors could influence the quality and acceptability of TIRS implementation using motorized equipment. Maneuvering indoors with motorized sprayers may be challenging, plus the added noise and CO_2 inside houses adds significant discomfort to operators and residents. Furthermore, in addition to the associated cost of preventive and/or corrective maintenance, motorized equipment has the added cost of fuel. Due to such limitations, motorized equipment is at a disadvantage compared to hand compression and rechargeable-battery sprayers.

The development of the IK Vector Control Super sprayer has brought important improvements to the classic IRS equipment, particularly in the context of urban vector control, with lighter design and integration of CFVs. Ongoing research in Merida, Mexico, performing TIRS in over 1,000 houses using the IK Vector Control Super sprayer has found that these devices operate very reliably (Vazquez-Prokopec et al., unpublished data). The lighter weight of the IK Vector Control Super sprayer was seen as the main improvement by operators. Additionally, operators felt less fatigue and found it easier to maneuver indoors due to the IK Vector Control Super sprayer's ability to be worn on the back, rather than on the side. As such, the IK Vector Control Super constitutes a valid alternative to classic IRS equipment for performing TIRS in urban areas.

In urban centers, where access to a power supply is not an issue, there may be benefits in using rechargeable-battery sprayers. All tested rechargeable-battery sprayers showed flow rates within WHO expected ranges, and very constant rates; all had discharges of over 100 liters with a single battery charge. Such high efficiency would be more than enough to cover a full day of TIRS application. In a randomized controlled trial evaluating the epidemiological impact of TIRS on *Ae. aegypti* in Merida, the average TIRS application time per house was 10 min (Vazquez-Prokopec et al., unpublished data). Additionally, reducing operator fatigue due to frequent pumping required by hand compression sprayers is another benefit associated with the rechargeable-battery sprayers. Furthermore, the

REC 15ABZ has 6 different regulator pressure options (0.5–6 bars) while the Solo 416 had 2 regulator pressure options. We did not assess the life of parts in rechargeable-battery sprayers, which may add significant costs to operational programs if repairs are frequently needed (e.g., the cost of replacing batteries would add significant costs to programs). Some of the technological advantages of rechargeable-battery sprayers could contribute to higher-quality spraying, which would overcome the low quality of spraying that is seen as a major driver of IRS failure in scaled-up interventions (Knapp et al. 2015).

While our work points to alternative options to the classic hand compression sprayers, future studies should include an assessment of acceptability of these devices by spray personnel, as well as an evaluation of sprayers in operational settings, to assess potential operational and economic value of their adoption.

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