A wearable wireless controlled-release device as the next-generation personal protection against vector-borne diseases

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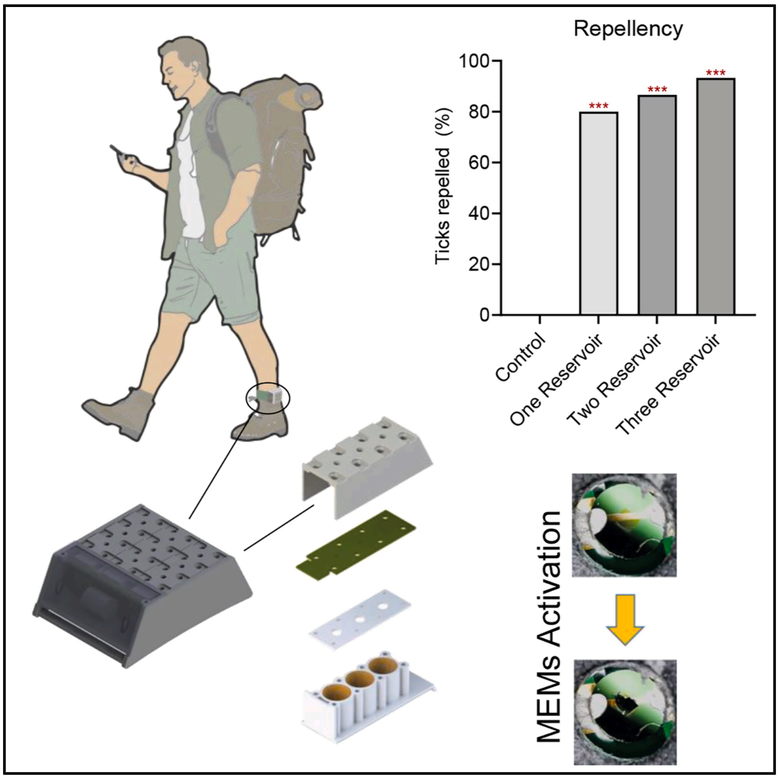
Graphical abstract



Authors

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In brief

D'hers et al. present the adaptive barrier controlled release device (AB-CRD), a wearable device that integrates electronics, micro-electro-mechanical systems, and wireless technology to enable on-demand, digitally controlled release of spatial repellents. The AB-CRD represents a step toward autonomous operation for maximum personal vector protection, achieving 88% tick repellency (*in vitro*).

Highlights

- Advanced electronics and MEMS offer dynamic release kinetics for optimal protection
- Digital multi-reservoir-controlled release device provides dose-dependent response
- Experimental results show repellency of up to 88% against *Dermacentor variabilis*
- The device improves user adherence for protection against vector-borne diseases

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A wearable wireless controlled-release device as the next-generation personal protection against vector-borne diseases

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SUMMARY

To address compliance issues with topical and spatial treatments and to improve protection against vectors, we present a wearable wireless device that integrates micro-electro-mechanical systems (MEMS) and electronics with advanced spatial repellents (SRs) as the next generation of personal protection. This platform, named the adaptive barrier controlled release device (AB-CRD), features Bluetooth connectivity and digital controls for the storage and selective release of SRs from multiple sealed reservoirs. Repellent release is initiated by discharging a capacitor to break a sealing membrane, allowing controlled diffusion. The AB-CRD was demonstrated in an *in vitro* assay against *Dermacentor variabilis* (American dog tick) as a proof of concept. Experimental results showed that dose escalation of a transfluthrin-based formulation produced increasing repellency, with mean values of 78%, 83%, and 88% for one, two, and three reservoirs, respectively. The AB-CRD represents a novel controlled-release platform for personal protection against vector bites, offering an efficient and adaptable solution.

INTRODUCTION

Lack of adherence and compliance with topical and spatial treatments to repel vectors remains one of the most elusive challenges in effectively preventing vector bites and protecting against vector-borne diseases, which affect millions of people worldwide.[1–7] Effective personal protection typically requires periodic reapplication of repellents.[8–12] Current topical repellents, such as DEET (N,N-diethyl-3-methylbenzamide), require frequent reapplication. Similarly, devices designed to disperse spatial repellents, including synthetic pyrethroids such as transfluthrin and metofluthrin, typically rely on cartridges with limited protection capacity, providing efficacy lasting only 4–6 h.[13–16] Furthermore, permethrin-impregnated fabrics also offer limited efficacy over extended periods.[14,17] Collectively, these limitations create significant gaps in continuous protection, thereby increasing the risk of disease transmission. Personal protection measures represent the last line of defense against vector-borne disease transmission, underscoring the importance of reliable and sustained protective methods.

Vector-borne diseases, particularly those transmitted by mosquitoes and ticks, represent complex global public health challenges. Mosquito-borne diseases alone affect approximately 500 million people worldwide and include malaria, Zika, chikungunya, dengue, and yellow fever.[18–20] Ticks, recognized as the leading vectors of zoonotic diseases in North America, transmit pathogens causing multiple illnesses, including Lyme disease, babesiosis, ehrlichiosis, Rocky Mountain spotted fever, anaplasmosis, Southern tick-associated rash illness, and tick-borne relapsing fever. Lyme disease alone accounts for over 50,000 confirmed cases annually in the US, while estimates of the actual incidence approach nearly half a million cases per year.[21–23] Current strategies for managing vector populations primarily involve environmental insecticide applications, barriers, and trapping

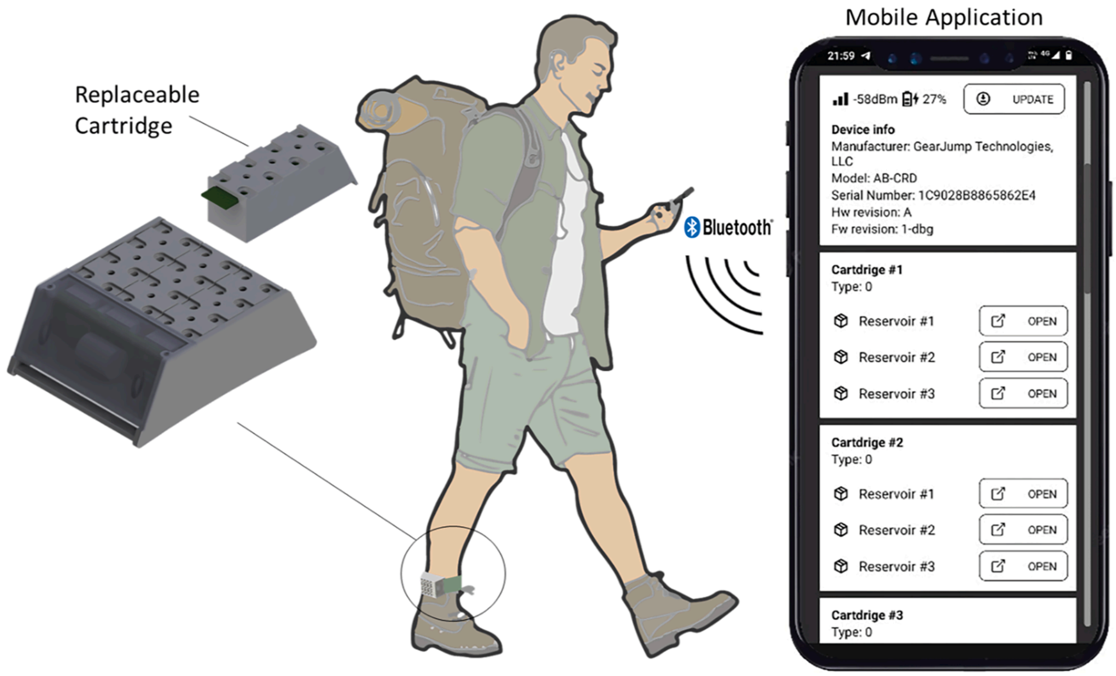

Figure 1. The AB-CRD in motion

The user triggers the activation of a MEMS actuator through the mobile app, which opens a specific reservoir in the cartridge to start the controlled release of the spatial repellent (SR). The system is powered by a battery-operated microcontroller that communicates via Bluetooth with the mobile app. Replaceable cartridges may include multiple active ingredients to customize protection against different vectors, e.g., mosquitoes, ticks, and flies.

methods, but these approaches often lack sustained individual-level protection.[24,25]

To address these critical gaps, there is an impending need for innovative personal protection solutions that can offer continuous, user-independent, low-compliance-barrier repellent wearable delivery systems capable of dynamically adapting to varying environmental conditions. Previously, we demonstrated controlled release devices (CRDs) that can be integrated for personal protection against mosquitoes.[8,9,11,16,26] Herein, we present an advanced wearable CRD platform that relies on the integration of wireless technology and micro-electro-mechanical systems (MEMS), named the adaptive barrier CRD (AB-CRD). The AB-CRD is a compact device (5 × 5 × 1.5 cm) that can be programmed and remotely activated using smartphone technology, offering intelligent dispersion of repellents from nine independently addressable reservoirs, as shown in Figure 1.

In this work, we demonstrated proof of concept of the AB-CRD, showing high repellency efficacy against *Dermacentor variabilis* (American dog ticks) in laboratory conditions. This first development step provides the basis for future studies, which will include testing against a wide variety of vectors.

Advancing technology development will allow fully autonomous operation, significantly enhancing personal protection against tick-borne diseases without the need for a user's intervention.

Thus, the AB-CRD represents a next-generation personal protection platform designed to deliver customized, dynamic protection.

RESULTS

Device architecture

The AB-CRD is comprised of three modules, as shown in Figure 2. The first module consists of the electronics system, which controls the AB-CRD in terms of initiating the controlled release process, as well as checks the status for each MEMS actuator; the second module consists of three arrays of swappable CRD cartridges, each containing three 1 mL reservoirs; and the third module is based on the software application that runs in a mobile device. The mobile application provides the interface between the user and the CRD module.

CRD electronics module

The CRD electronics module relies on a micro-controller for Bluetooth communication and the power electronics modules. The Bluetooth communication submodule is responsible for sending and receiving data from and to a mobile device. The receiving data consist of commands received from the paired mobile device that informs which MEMS actuator is available for activation, allowing independent controlled release of an active ingredient from a specified reservoir. A status signal from the AB-CRD to the mobile device is sent to verify that a specified MEMS actuator was activated by measuring the continuity of the fuse actuator. The power electronics submodule consists of a resistor-capacitor (RC) circuit that integrates a charging capacitor to generate a high-power, short electric pulse (∼10 mJ, 1 μs) to be applied to the MEMS actuators. A high-power transistor switch is used to direct the activation to any specific MEMS actuator. The electronics module

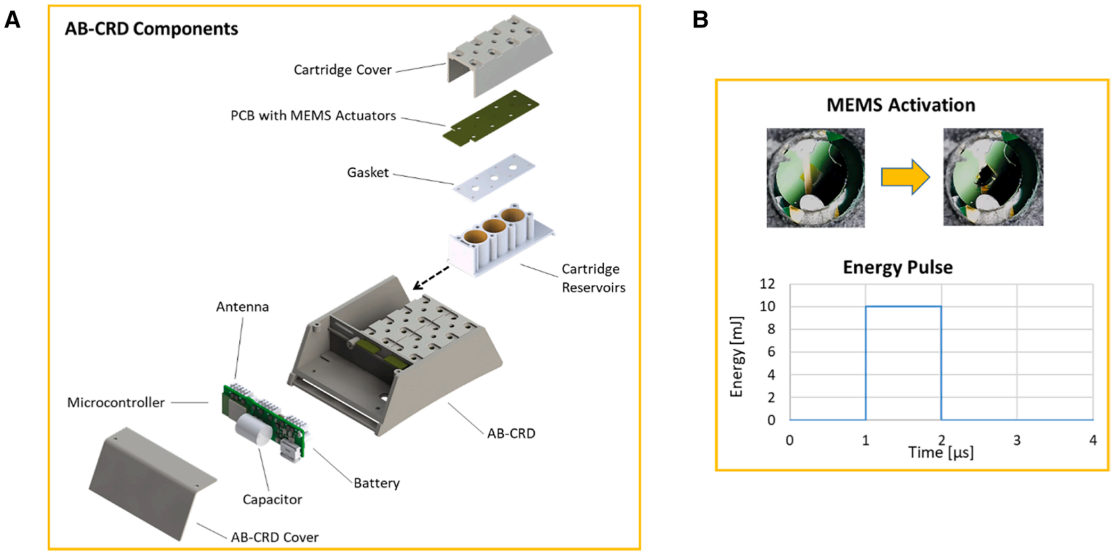

Figure 2. AB-CRD components and MEMS actuator activation
(A) Exploded view of AB-CRD.
(B) MEMS activation.

operates using a USB-rechargeable lithium-ion battery to power the activation of the nine MEMS actuators. In the present design, a battery capacity of 3,000 mAh is sufficient to burst 9 membranes.

CRD module

The CRD design consists of three hot-swappable cartridges. Each cartridge includes three 1 mL reservoirs. The cartridges were manufactured using 3D printing based on a stereolithographic apparatus (SLA) to define a high-precision structure in a thermoset polymer.

MEMS actuator design

The MEMS actuator design is based on the electro-thermally induced structural failure actor (ETISFA), consisting of an electric fuse deposited on a suspended membrane.[27] Once an electric current is applied, an electro-thermal shock bursts the suspended silicon nitride membrane open, allowing the controlled release of the active ingredient to take place.[26]

Mobile application

The mobile application allows the user to activate the AB-CRD remotely from a mobile device via Bluetooth communication. The application was programmed in Java, compatible with the Android operating system. The mobile application requires Bluetooth recognition of the AB-CRD. The application provided a user interface for the following functions: (1) access to each of three cartridges, (2) obtain status information for each of the three membranes per cartridge pre-and post-activation, and (3) allow independent MEMS activation by selectively bursting each of the sealing membranes sealing a reservoir per user's request. The application was designed to run in the background of the mobile application, which eventually would allow for the integration of additional features, including GPS location, internet access, access to publicly available environmental information (e.g., temperature, wind, and humidity), and optionally other users' past choices per given location when selected.

Device operation

The user is able to run the mobile application and manually select a specific reservoir per cartridge, as well as verify the status of each MEMS actuator pre- and post-activation. The user is also able to verify whether a given cartridge was connected. Once the membrane for a given reservoir is burst, the release process is initiated. Treatment duration was tailored by adjusting the controlled release rate and the volume capacity of each reservoir. The release rate was defined by the volatilization of the formulation and the membrane opening (1 mm^2). The mobile application kept track of the remaining protection time using a simple linear estimator.

One unique aspect of the AB-CRD is its ability to activate a single or multiple MEMS actuators in a given activation sequence, providing a unique opportunity to control the release kinetic profile. For example, a user may need to have a low release rate for minimum protection, thereby only activating a single MEMS actuator for controlled release from a single reservoir. In a different scenario characterized by higher vector pressure, a user may want to have a high release rate for maximum protection, thereby activating several MEMS actuators at once. A combination of active ingredients (e.g., synthetic or natural pyrethroids) may also be implemented for broader-spectrum protection. For example, one set of cartridges may contain a spatial repellent, e.g., transfluthrin, whereas another set of cartridges may contain a different repellent, e.g., metofluthrin, and another cartridge may contain natural repellents, e.g., nootkatone. Therefore, it may be possible to program the AB-CRD to combine AIs to maximize protection according to a given scenario. Figure 3 shows the manual operation mode.

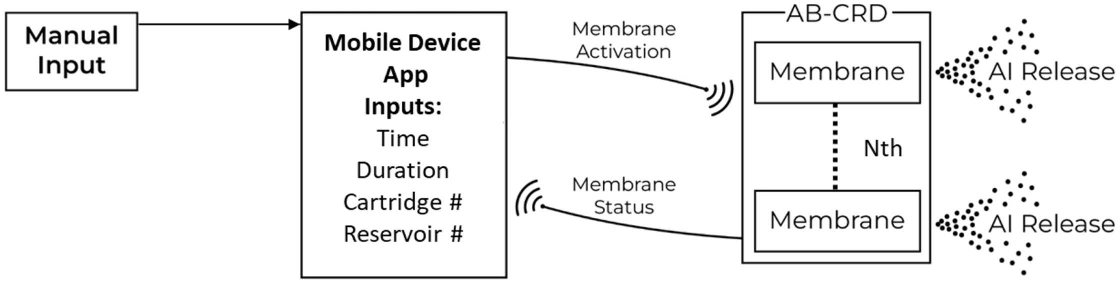

Figure 3. AB-CRD manual operation mode

Users manually enter time, protection duration, cartridge number(s), and reservoir number(s).

Experimental results

An entomological study was performed to evaluate the efficacy of AB-CRDs against ticks in an *in vitro* setting (please refer to the methods section for details). Three parameters were considered, each assessing different visible behavioral changes: (1) climbing of ticks, measured in cm/s; (2) repellency, calculated by the proportion of ticks that failed to reach the top zone and stayed divided by the total number of ticks in the group[28]; and (3) mean height observed, measured in cm as the mean height at which a tick was found during the trial. Additional detailed data are provided in the supplemental methods.

A Mann-Whitney U test was used to quantify changes in continuous measures (movement speed and mean height observed). Effect sizes ($r > 0.50$ considered large) were calculated from Pearson's r for pairwise comparisons of controls to repellent groups. Groups were compared with a Fisher's exact test for proportion measures and repellency. GraphPad Prism, v.10.0.2 (GraphPad Software, San Diego, CA, USA), was used to run tests and make graphs.

Experimental results showed significant comparisons across controls and repellent groups. Significant differences among reservoir groups were shown with bracketed lines indicating the groups compared with associated *p* values.

All AB-CRD tests showed significant efficacy with each parameter. A dose-dependent response was observed. The movement speed of ticks decreased relative to controls as the dose increased (minimum $r = 0.76$), as shown in Figure 4A. Repellency results are shown in Figure 4B. It is possible to observe that ticks from the control group were not repelled. The mean height at which ticks were found across the trial is shown in Figure 4C. Significant dose-escalation responses were observed (minimum $r = 0.83$).

A summary of experimental results shows a clear dose escalation repellency response, obtaining mean repellency values of approximately 0% (control), 78% (one reservoir), 83% (two reservoirs), and 88% (three reservoirs), correspondingly. Climbing speed was measured to show activity inhibition. Experimental results showed dose-escalation responses in the mean climbing speed of approximately 0.42 (control), 0.17 (one reservoir), 0.13 (two reservoirs), and 0.06 (three reservoirs) cm/s. Finally, the study showed the effects on the mean climbed height, demonstrating a combination of inhibition and repellency. Experimental results showed dose-escalation responses of approximately 28 (control), 4 (single reservoir), 2.5 (two reservoir), and 0.8 (three reservoirs) cm.

Toward autonomous protection

A more advanced version of the AB-CRD will be implemented in the future based on the semi-autonomous mode, allowing us to operate the AB-CRD with a high level of autonomy once a threat level is selected (e.g., low, medium, or high), as shown in Figure 5A.[29,30] In this case, the rate will be dynamically adjusted according to algorithms that will take multiple environmental variables into account to decide the number of MEMS actuators to be activated, as well as the selection of the active ingredients to be used for a targeted protection level. Such variables may include temperature and humidity conditions, as well as GPS location, date, and time of the day. These multiple variables will be inputs for the algorithms that will lead to the creation of an aggregated dataset, ultimately resulting in an output signal for optimal selection of the active ingredients to use, given the required rate to target a specific vector species. Therefore, the ability to operate in a semi-autonomous mode will allow an unprecedented level of protection that will further decouple the dependence of the user's adherence and compliance from their own personal protection treatment.

Furthermore, in the semi-autonomous mode, the release kinetic profile may be customized according to the user's potential exposure.[31–34] For example, the user may start by selecting the targeted vector, e.g., mosquitoes, ticks, sandflies, etc. The vector species may also be selected, e.g., *Ixodes scapularis* or *Anopheles gambiae*. The user may then choose the mode and the intensity of operation, e.g., minimum, moderate, or maximum protection. Such profile customization will provide a specific programming sequence of the MEMS actuators to maximize the level of protection. More importantly, these approaches will improve protection, as the compliance needed for a given treatment will be optimized by the implementation of machine learning (ML) algorithms, e.g., convolutional neural networks (CNNs), to include a training dataset based on multiple users' past and present activity.

Future versions of the AB-CRD may also lead to a fully autonomous mode, which will rely on AI, as shown in Figure 5B. Implementation of such advanced algorithms will allow us to optimize release rates based on prior data that were collected by reports from multiple users, such as overall performance against a specific target species, as a function of the multiple environmental

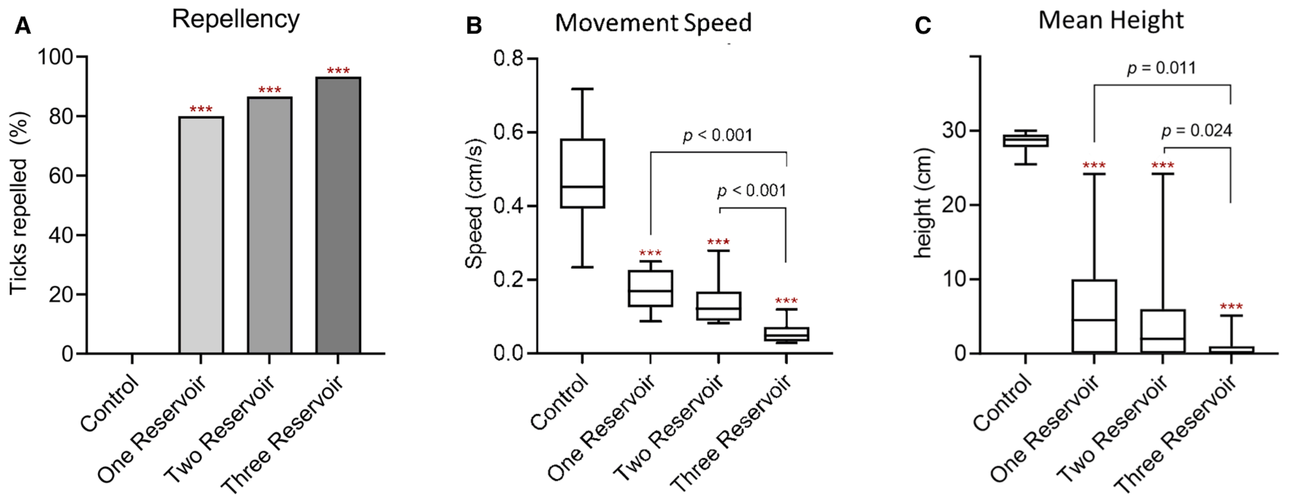

Figure 4. Experimental results
Repellency and behavioral changes were studied in the *in vitro* study.
(A) Repellency results.
(B) Movement speed distribution (boxplot).
(C) Mean height distribution (boxplot).
Significant comparisons across controls and repellent groups are identified in the graphs with asterisks (*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$, Mann-Whitney U test).

input variables, similar to the semi-autonomous mode. This mode will continually improve protection based on the historical performance of multiple users to autonomously optimize the release rate for maximizing personal protection.

The AB-CRD represents a paradigm shift in personal protection against vector threats. A controlled release profile can therefore be tailored by taking multiple variables into account within the environment.

DISCUSSION

This work represents a critical first step toward autonomous protection against vector threats, thereby laying the foundations for a paradigm change in personal protection. The AB-CRD provides an innovative solution to dynamically personalize and optimize vector protection strategies based on individual users and environmental conditions. One of the key innovations of the AB-CRD is the ability to customize protection dynamically.

Furthermore, the AB-CRD's connectivity with mobile devices brings an unprecedented modality to personal vector protection, enabling user control over the release of different active ingredients. With the ability to select multiple active ingredients and customize overall release kinetic profiles, users can tailor their protection to specific vectors, thereby maximizing protection.

Another innovation of the AB-CRD is the capability for integration with ML algorithms for semi-autonomous and autonomous operations. The future implementation of these advanced modes has the potential to revolutionize personal protection against vectors by continually learning and optimizing release rates based on past and current users' performances.

Device cost and users' willingness to invest in their own protection must be addressed in future epidemic treatment analyses to offer feasible scalable solutions.[35] The AB-CRD will provide a solution to the growing threat of vector-borne diseases and their expanding geographical distribution influence. Device design and ergonomics are important factors to be addressed in the next development phases to guarantee ease of use, wearability, and user acceptance. Battery usage will be optimized for expected continuous use. Safety and reliability studies according to regulatory requirements will be a necessary step for product development.

The unique integration of controlled release technology, microelectronics, MEMS, and mobile technology provides an unprecedented level of dynamic and targeted protection against various deadly vectors, including ticks, mosquitoes, and sandflies, which affect millions of people worldwide. The AB-CRD provides a significant advancement in personal protection, opening up the possibility for integration with AI embedded in mobile technology to optimize personal protection. The AB-CRD represents a breakthrough platform in the prevention of vector-borne diseases globally.

METHODS

CRD module manufacture

Stereolithography files are available in the supplemental information. The top of the structure includes a defined ledge on which a gasket is placed to provide a hermetic sealing and prevent any leakage. The printed circuit board (PCB) was secured and tightened against the reservoir gasket using Torx fasteners (size 7). The PCB included the MEMS actuators adhered to the board using UV-cured epoxy and connected to the copper tracks to access each reservoir. The PCB included 1-mm-diameter through-holes that acted as vias to provide

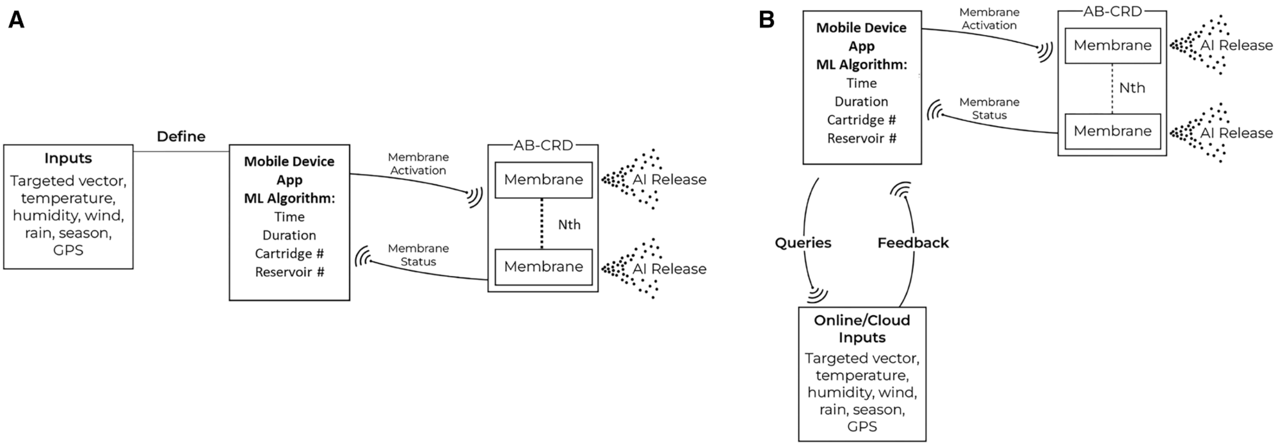

Figure 5. Advanced operation modes

(A) Semi-autonomous mode. Users enter target vector(s). Weather and GPS data are input from online sources.

(B) Autonomous mode. ML algorithms obtain all inputs, including the target vector(s) from online sources or other users' selections, to determine the optimal control release profile.

access to the reservoirs. The MEMS actuators were effectively designed to act as sealing membranes of the vias and as one-time activation valves.

MEMS actuator manufacturing

The MEMS actuators were defined in a 3 mm single-crystal silicon (SCS) circular chip. A PCB was manufactured to include the electrical connections, as well as the vias. The MEMS chips were placed on the PCB, geometrically aligning the suspended silicon membranes with the through holes (vias). Each MEMS actuator consisted of three layers with tantalum-copper-tantalum defined as a 100-μm-wide electrode that ran across a standing silicon nitride 750 × 750 μm membrane. The electrode was defined using an evaporator that deposited the three layers as follows: 20 nm Ta adhesion layer, 200 nm Cu layer, and 20 nm Ta protective layer. Subsequently, photolithography was performed to transfer the selected pattern into the metal layers. The chip manufacturing relied on standard bulk micromachining techniques based on an anisotropic KOH etch to define the standing silicon nitride membranes.[36] Each chip was fixed to the PCB using a UV-cured epoxy. Each PCB track was connected to each electrode on the chip using highly conductive silver paint with a volume resistivity of 2E−4 Ω·cm (product no. 16062, Ted Pella, USA).

MEMS actuator integration

The backside of each plastic cartridge contained a small loading inlet through which the formulated active ingredient (transfluthrin) was injected into a reservoir and subsequently sealed using the UV-cured epoxy. A small cellulose matrix was integrated inside each reservoir to absorb and hold the active ingredient and prevent any spillage. Each cartridge included a plastic top covering case to protect the PCB and MEMS components. The front end of each cartridge included a flat connector that fit directly into the spring-loaded connector for direct and facile connection to the electronics module. Figure 2A shows the multiple components of the AB-CRD. Figure 2B shows the MEMS actuators pre- and post-activation.

Experimental methods

An entomological study was performed to evaluate the efficacy of AB-CRDs against ticks in an experimental setting as previously described, shown in Figure 6.[37] This *in vitro* study assessed behavioral changes relative to the tick's natural tendency to climb. Three 30 cm sticks were placed vertically (distanced 2.5, 30, and 57.5 cm from the device) inside a transparent open-vertex box. Controls were performed in the absence of the AB-CRD device. In the active experiment, the AB-CRD reservoirs were loaded with the formulation based on 30% transfluthrin and 70% isopropyl alcohol (w/w). The device was placed on the inner sidewall of the chamber and wirelessly activated 20 min prior to tick introduction. A dose-escalation test was performed to test one, two, and three reservoir release systems. Five replicates were performed for each group (n = 15 ticks per group, 60 ticks total). Each adult female *Dermacentor variabilis* tick begun the trial at the bottom of each of the three sticks, and their behavior was observed for 10 min. The movement of each tick was digitally recorded using a video camera with a tracking software (Noldus Information Technology's EthoVision XT, v.18.0). The Cartesian x, y coordinate system was utilized for parameter comparisons across the three species groups. An inclusion/exclusion test was performed prior to repellency trials to ensure that ticks climbed an unexposed stick for subsequent use.

The actual reservoir used had 1 mL with a release rate of approximately 500 ng/h of AI and was expected to provide protection for up to 30 days after membrane bursting.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Noel M. Elman (noel@gearjumptech.com).

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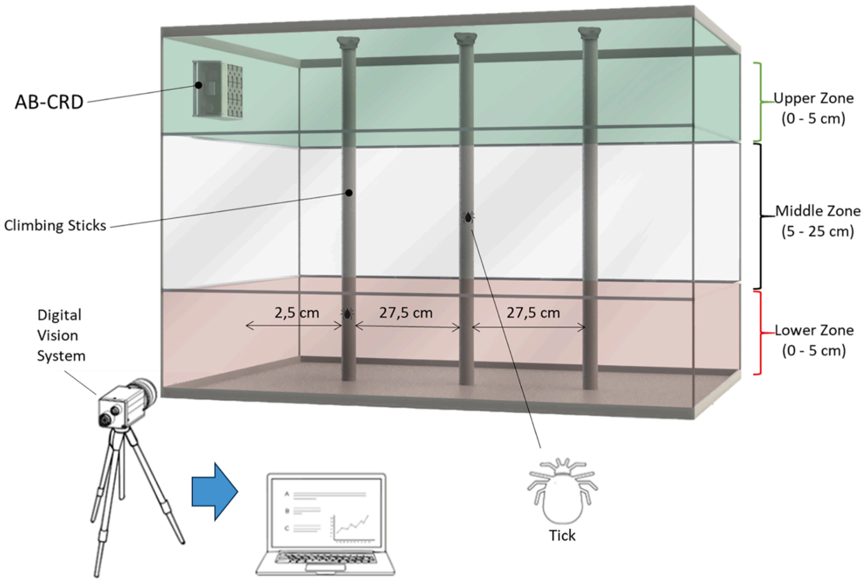

Figure 6. Experimental setup for *in vitro* study

The AB-CRD was attached to the left inner panel of a transparent box. Three evenly spaced vertical sticks were placed to induce the ticks' natural climbing as a function of treatment (active) vs. no treatment (control). Experimental data were obtained using a digital view system.

Materials availability

This study did not generate new unique reagents.

Data and code availability

- Data are available from the lead contact, Noel M. Elman (noel@gearjumptech.com), upon request.
- No code was generated in this study.
- Stereolithography files are available as supplemental information.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact, Noel M. Elman (noel@gearjumptech.com), upon request.

ACKNOWLEDGMENTS

The authors would like to dedicate this work to the memory of Mr. Meredith Metzler, who will be greatly missed. The authors would also like to thank Mr. Kevin Smith as a representative of Envu Environmental Sciences US LLC for providing the technical transfluthrin to conduct the research. His enthusiasm and corporate contribution are greatly appreciated. This research work was supported by the Department of Defense (DOD) Tick-borne Disease Program from the Congressional Directed Medical Research Program, grant #W81XWH1920028, and by the Deployed Warfighter Protection Program, grant #W911SR2210011. S.M.R. and E.L.S. were supported in part by Centers for Disease Control and Prevention grant number U01CK000661 (New England Center of Excellence in Vector-borne Diseases). S.D.'s work was developed at the Computational Mechanics Lab of the Instituto Tecnológico de Buenos Aires. The funders had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. This article reports the results of research only. Mention of a proprietary product does not constitute an endorsement or a recommendation by the authors, the CDC, or the DOD for its use.

AUTHOR CONTRIBUTIONS

E.L.S. and S.M.R. conducted the entomological studies. S.D., M.P., S.M.R., and N.M.E. were involved in planning and supervising the work. S.D., E.L.S., and S.M.R. processed the experimental data and carried out the analysis. S.D., E.L.S., S.M.R., and N.M.E. drafted the manuscript. M.M. fabricated the MEMS devices. D.G.M. contributed to the validation and testing of the MEMS devices. D.I. designed and produced the communications and electronics modules as well as the operational application. S.D., D.I., and N.M.E. designed, manufactured, and assembled the AB-CRD. S.D. and D.I. tested the mechanical and electronic components. S.D., E.L.S., S.M.R., and N.M.E. contributed to the manuscript. All authors discussed the results and provided feedback on the manuscript.

DECLARATION OF INTERESTS

N.M.E. is CEO and founder of Gearjump Tech and has a patent application related to the platform AB-CRD. S.D. is CTO of Gearjump Tech.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used OpenAI (2025) to improve academic writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

SUPPLEMENTAL INFORMATION

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