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Nano/micromotors for security/defense applications. A review

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The new capabilities of man-made micro/nanomotors open up considerable opportunities for diverse security and defense applications. This review highlights new micromotor-based strategies for enhanced security monitoring and detoxification of chemical and biological warfare agents (CBWA). The movement of receptor-functionalized nanomotors offers great potential for sensing and isolating target bio-threats from complex samples. New mobile reactive materials based on zeolite or activated carbon offer considerable promise for the accelerated removal of chemical warfare agents. A wide range of proof-of-concept motor-based approaches, including the detection and destruction of anthrax spores, 'on–off' nerve-agent detection or effective neutralization of chemical warfare agents have thus been demonstrated. The propulsion of micromotors and their corresponding bubble tails impart significant mixing that greatly accelerates such detoxification processes. These nanomotors will thus empower sensing and destruction where stirring large quantities of decontaminating reagents and controlled mechanical agitation are impossible or undesired. New technological breakthroughs and greater sophistication of micro/nanoscale machines will lead to rapid translation of the micromotor research activity into practical defense applications, addressing the escalating threat of CBWA.

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1. Introduction

The rapid progress in nanotechnology has led to the development of powerful synthetic micromotors that convert energy into movement and are able to perform advanced tasks at the micro- and nano-scales.[1–6] Such a use of nano/microscale motors to power tiny machines is an exciting research area due to a wide range of potential applications. These micromotors move liquids by converting different sources of energy into mechanical force and motion and represent a major step towards the development of practical nanomachines. Man-made nano/microscale motors, based on a variety of propulsion mechanisms, have thus been developed in recent years.[1]

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These include chemically-powered micro/nanomotors that harvest their energy from the surrounding fuel, and fuel-free motors powered by external stimuli (*e.g.*, magnetic and acoustic fields). Modern artificial micromotors display a high speed and power, along with precise motion control, cargo-towing and self-mixing abilities, chemotactic and collective behaviors, and facile surface modification.[1–6] Multi-functional micromotors that incorporate different modalities within a single nanovehicle have been described. The new capabilities of man-made micromotors have opened a new horizon for the defense community due to their diverse potential applications, as indicated from a variety of recent proof-of-concept demonstrations.[7–12]

The continuous threat of exposure to chemical and biological warfare agents on both the battlefield and through terrorist attacks has led to a recent surge in research aimed at the detection and decontamination of these highly toxic compounds. Scientists are thus devoting considerable efforts to develop new efficient approaches for detecting and eliminating weapons of mass destruction (WMD). Chemical and biological warfare agents (CBWA) have been used as WMD because of their proclivity to cause morbidity and mortality in large numbers.[13,14] CBWA agents dispersed as a gas, liquid or aerosol can cause large-scale mortality, morbidity, and incapacitate a large number of people in the shortest possible time.[13,14] Taking recent technological advances into consideration, easy access to raw materials, and the ready availability of technical information it is not difficult for terrorists to use chemical warfare agents (CWA) to achieve their goals.[13–15] As a consequence, intense research efforts have been devoted to develop novel methodologies for detecting and destroying WMD. For example, surface acoustic wave devices,[16] enzymatic assays,[17] electrochemical sensors,[18] interferometry[19] and gas chromatography-mass spectrometry[20] have been developed for WMD detection. However, each of these methods presents at least one of the following limitations: slow responses, limited selectivity and false positive readings, low sensitivity, operational complexity, non-portability, and difficulties in real-time monitoring. Current methods for the decontamination of CWA involve the use of strong oxidants,[21] enzymatic biodegradation,[22] atmospheric pressure plasma,[23] and photocatalytic[24] and incineration methods.[25] These procedures have their own drawbacks, such as lack of stability, strong environmental impact, and high temperature, which make them unsuitable for large scale field-based detoxification of CWA. Thus, there are urgent needs to develop rapid and reliable detection and screening methods for chem-bio threats to promote timely medical treatment and effective CBWA decontamination to reduce the mortality rate.

Recent advances in micro/nanoscale machines indicate their potential to address events that threaten our security. New nanomotor-based approaches for "on-the-fly" detection measurements and 'capture–transport–release' separations provide an efficient approach for detecting and isolating CBWA from raw samples. Autonomous mobile nanomachines hold considerable promise for monitoring inaccessible locations or hostile environments and for using chemotactic search strategies to trace plumes of chemical threats to their source. Changes in the swimming behavior in the presence of hazardous chemicals could offer direct visualization of potential threats.[26–28] The coupling of autonomous self-propelled microplatforms with advanced reactive materials or specific surface functionalization has provided new opportunities towards efficient motion-based detoxification processes. These micromotors extend the reach of the active reactants throughout the solution *via* mixing and motion and lead to greatly reduced reaction times. Such micro/nanomachine-based detection and neutralization platforms could address some of the major obstacles associated with traditional methodologies used in the defense sector. The many recent proof-of-concept experiments exemplify the versatility and capabilities of nanomachines in the defense arena and are indicative of their considerable potential in a wide range of security applications.

This article reviews recent advances in using modern micro/nanoscale motors for a variety of defense applications and highlights the opportunities and challenges of this important field. Particular attention will be given to new motion-based protocols for effective detection and isolation of chem-bio threats and to 'on-the-fly' procedures for enhanced removal or detoxification of CBWA. Our goal is to educate the nanotechnology community about the opportunities in the defense arena and to update the security sector about the potential of nanoscale machines for diverse defense applications. As will be illustrated below, the new capabilities and functionalities of man-made micro/nanoscale machines open up the door for powerful mobile platforms to counter potential threats in connection to diverse security applications.

2. Chemical and biological warfare agents

2.1. Classification

CWA possess different characteristics and belong to various classes of compounds with pronounced physiochemical, physiological, and chemical properties. The CWA can be classified as non-persistent or persistent.[13,14] Blood or choking agents fall into the category of non-persistent CWA due to their high volatility, while nerve agents, blister agents, or arsenicals, come under the category of persistent CWA.[13,14] In this review, we will discuss mainly four types of CWA (refer to Table 1 and Fig. 1). Due to the high toxicity of CWA, researchers have been utilizing CWA simulants, which are less toxic than the actual CWA agent, to examine, study, and understand the chemical reactivity of certain functional groups.[29] A simulant is considered ideal if it mimics key chemical and physical properties of the chemical agent without its associated toxicological properties.[29] A number of compounds have been used as CWA simulants since no specific compound is ideal because a single simulant cannot adequately represent all properties of a given CWA.

Vocabulary

Biological warfare agent	Viruses, bacteria, other microorganisms, or toxins derived from living organisms that cause death or disease in humans, animals or plants
Blood agents	Agents that inhibit certain specific enzymes particularly cytochrome oxidase and influence various metabolic processes
Blister agent	Blister agents, known also as vesicants, and have ability to cause several chemical burns resulting in large, painful water blisters
Bubble propulsion	A force causing movement which results from bubble detachment
Catalytic motors	Motors powered by catalytic reactions of a fuel
Chemical warfare agent	Chemical substances which are intended for use in warfare to kill, seriously injure, or incapacitate people
Choking agent	Agents that injure an individual mainly in the respiratory tract and cause death due to lack of oxygen
Decontamination	The process of removing, neutralizing, or destroying harmful substances
Janus particle	A two faced microparticle
Nanomachine	A nanoscale device that performs a task
Nanomotor	A nanoscale device capable of converting energy into movement and forces
Nanoremediation	Use of reactive nanomaterials for transformation and detoxification of pollutants
Nerve agent	Organophosphorus (OP) compounds that bind irreversibly to the enzyme acetylcholinesterase
Propulsion	A force causing movement
Simulant	A compound or substance which mimics the chemistry and reactivity of a compound of interest, but is less toxic

Pathogenic microorganisms, such as bacteria cells, bacterial spores, viruses, plants, and algae that produce toxins, are considered as biological warfare agents (BWA) if the toxins are extremely potent, or capable of being dispersed to incapacitate or kill thousands of humans.[30] The U.S. Centers for Disease Control and Prevention (CDC) has categorized many biological agents into three classes, A, B, and C, with A being the highest priority. Category A agents, such as *Bacillus anthracis* and *Clostridium botulinum*, are easily disseminated and may result in high mortality rates. Indeed, anthrax, the disease caused by *Bacillus anthracis*, was most recently used by bioterrorists in the United States in 2001 and remains one of the most likely candidates for a biological assault. Refer to Table 2 for more details about types of BWA, routes of infection and their possible release mechanism.

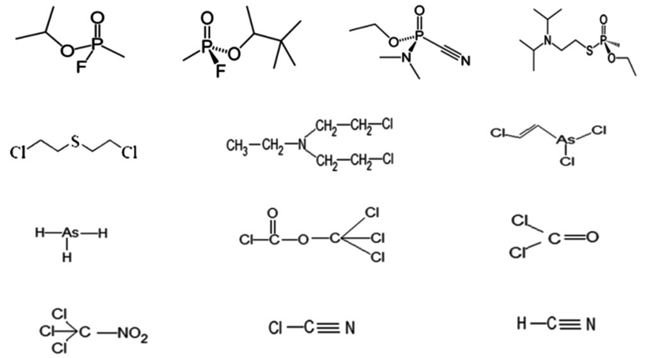

Fig. 1 Structures of different CWA.

2.2. Present defense requirements

The use of CBWA remains a major threat despite the chemical weapon convention (CWC) and biological weapon convention (BWC) that prohibit their use. The terrible events of 1995 in the Tokyo subway and the post-September 11 anthrax attacks in the United States revealed the ease with which these weapons can be utilized. As a result of this continuous threat, there are tremendous demands for innovative field-portable tools capable of detecting and destroying CBWA in a faster, simpler, and reliable manner at the site of terrorism, with the ultimate goal of finding defensive measures against these agents. For example, a rapid and sensitive detection of CBWA could provide an early alarm of their release, hence minimizing further spread and civilian casualties. CBWA need to be detected and identified and isolated at extremely low concentrations in complex, ever-changing backgrounds in near real time. Clearly, existing sensing and monitoring systems do not meet the needs of the military or civilian sectors for the purpose of "detect to warn". They suffer from relatively poor sensitivity, false positives, and lengthy response times. On-site efficient decontamination and rapid elimination of CBWA reduce the chances of their spread and cross contamination.

Table 1 Types of chemical warfare agents

Agent type	Effect	Examples
Nerve	Binds irreversibly to acetylcholinesterase inhibiting acetylcholine regulation	G Series: tabun, sarin and soman V series: VX
Blister or vesicant	Produces blistering of the skin and affects mucous membranes and eyes	Sulfur mustard and nitrogen mustard
Choking or pulmonary	Damages respiratory track and lungs	Chlorine and phosgene
Asphyxiant or blood	Interferes with the adsorption of oxygen into the bloodstream	Hydrogen cyanide
Tear or lachrymatory	Induces tearing causing irritation to the eyes and skin	Tear gas
Incapacitating	Produces mental or physiological effects preventing normal activity	Psychedelic agent BZ

Table 2 Types of biological warfare agents

Disease/agent	Stage	Route of infection	Possible release
Anthrax/*Bacillus anthracis*	Spores	Skin wounds, inhalation, ingestion	Spores as aerosol
Plague/*Yersinia pestis*	Bacteria	Fleas Aerosol	Aerosolization or release of infected fleas
Tularaemia/*Francisella tularensis*	Bacteria	Aerosol	Aerosolization of the bacteria
Glanders/*Burkholderia mallei*	Bacteria	Aerosol	Aerosolization of the bacteria
Cholera/*Vibrio cholerae*	Bacteria	Oral	Contamination of food and water sources
Small Pox/*Variola major*	Virus	Aerosol	Aerosolization of virus
Ebola/*Haemorrhagic fever*	Virus	Aerosol	Aerosolization of virus

3. Propulsion of micromotors

The remarkable performance of biomotors, with a variety of locomotive strategies, has provided an inspiration for the development of man-made nanoswimmers, operating on locally supplied fuels and performing various tasks. The propulsion of these tiny artificial micromotors through fluid environments is one of the most exciting fields of nanotechnology. A variety of fuel-driven and fuel-free microscale motors offer great promise for different security applications. Artificial micromotors harnessing different sources of energy for their locomotion have thus been described, including chemical energy,[31–45] surface tension force,[46,47] Marangoni effect,[48,49] self-electrophoresis,[50] magnetic field photonic[51–55] or acoustic[56] or external electric field,[57] self-thermophoresis,[58,59] and living motile cell.[60,61] Table 3 provides a general summary of chemically-powered micromotors along with the different types of catalyst/metal used for their propulsion. The majority of nanovehicles used so far for defense applications are based on fuel-powered catalytic motors and are mass produced using the template electrodeposition strategy. Two classes of mechanisms, phoretic and bubble thrust, are largely responsible for the propulsion of such catalytic micro- and nanomotors. In phoretic mechanisms, the catalytic reaction results in a gradient (concentration, electrical, temperature) in the vicinity of the motor, and this gradient induces the motion. For example, bimetallic nanorods (Au/Pt) are chemically propelled in aqueous solutions by the catalytic decomposition of hydrogen peroxide which leads to an internal flow of electrons from one end to the other end of the nanowire, along with the migration of protons in the double layer surrounding the wires.[62] Mallouk *et al.* found that the speed of a bimetallic nanorod depends on the mixed potential of individual catalytic metals.[63] These nanowire motors operate only in low ionic-strength media. The bubble propulsion mechanism involves the generation of gas by the catalytic decomposition of the fuel which leads to an efficient autonomous motion.[11,31–33,64] For example, tubular microengines rely on the decomposition of hydrogen peroxide at the inner Pt layer to generate an oxygen bubble thrust. Such microengines have been widely used for biodefense applications owing to their compatibility with diverse real environmental and clinical samples. Fig. 2 and 3 provide general summaries of the different types of micromotors that have been developed for use in the defense sector.

Table 3 Summary of different types of chemically-powered micromotors based on different catalysts, fuels and propulsion mechanisms

Chemically powered micromotor	Type of catalyst/metal	Fuel	Propulsion mechanism	Ref.
Tubular	Catalase	H_2O_2	Bubble propulsion	31, 32
Tubular	Pt/Pt nanoparticle-CNT	H_2O_2	Bubble propulsion	11/33
Microparticle	Mn	H_2O_2	Bubble propulsion	34
Microparticle/Janus micromotor	Ag	H_2O_2	Bubble propulsion	34, 35
Tubular	TiO_2	H_2O_2	Light induced	36
Tubular	Zn	Acidic media	Bubble propulsion	37
Janus	Pt black/Pt	$NaBH_4/H_2O_2$	Bubble propulsion	6/38
Janus capsule	Pt nanoparticle	H_2O_2	Bubble propulsion	39
Janus microspheres/microparticle	Al and Pd	Strong acidic and alkaline medium/H_2O_2	Bubble propulsion	40, 41
Janus micromotor	Ir	Hydrazine (N_2H_4)	Osmotic effect	42
Microparticle	Mg	Water containing chloride	Bubble propulsion	43
Alloy microsphere	Al alloy	Water	Bubble propulsion	44
Nanorods	Au–SiO_2	$NaBH_4$, KBH_4 and H_2O_2	Bubble propulsion	45
Metal–organic framework/camphor disk	—	—	surface-tension gradient	46, 47
Polymer gel	—	—	Marangoni effect	48, 49
Copper–platinum (Cu–Pt) rod	—	Br_2 and I_2	Self-electrophoresis	50
Platinum–gold or ruthenium–gold bimetallic rods	Au, Pt, Ru	H_2O_2	Self-electrophoresis	62, 63

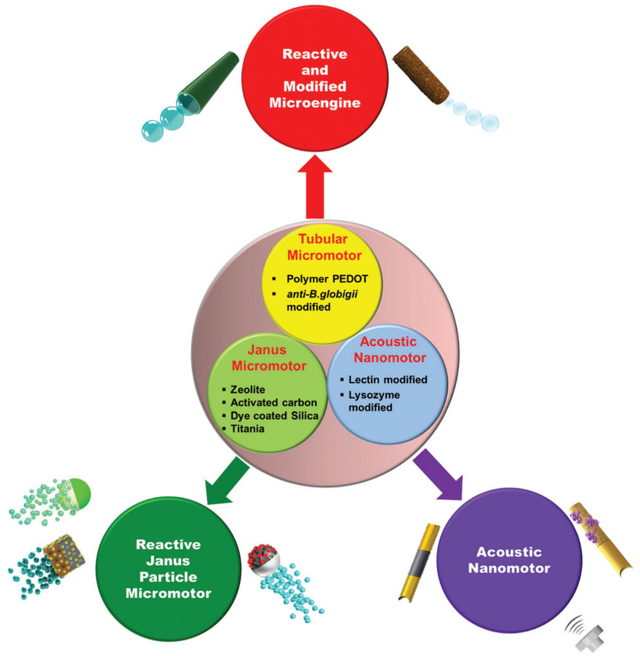

Fig. 2 Micromotors used for defense applications.

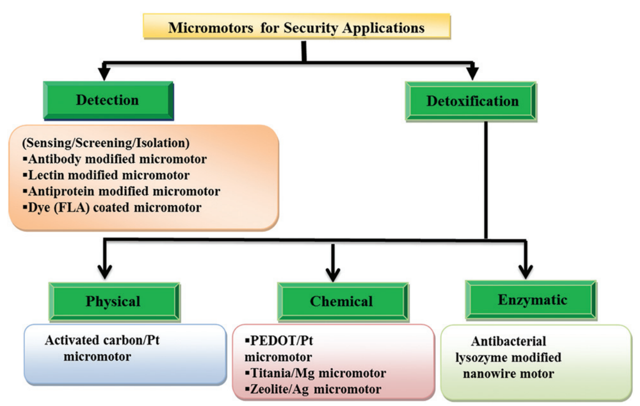

Fig. 3 A comprehensive account of micromotors used in defense applications.

4. Security monitoring using nanomotors

Recent proof-of-concept studies demonstrated the versatility of functionalized micromotors in defense monitoring applications. Such applications also benefit from the ability of these tiny submarines to penetrate otherwise inaccessible locations, and be deployed and function in remote areas. Such tiny machines add a new dimension based on motion assisted detection and isolation processes, leading to new sensing protocols, and have the potential to reduce the response time. Here we outline recent advances in the defense/security field.

4.1. Isolation and detection of CBWA

In CBWA scenarios, the major objective of detection is to warn about sudden changes and incoming threats, to establish adequate protective measures (protective masks and clothing as well as medical treatment), to map the contamination area and to start decontamination processes. Therefore, the development of a reliable on-site detection system for these agents is a prime objective worldwide. Hand held on-site detection systems for the detection of CWA work on the principle of ion mobility spectrometry, flame photometry, infrared spectroscopy, flame ionization, Raman spectroscopy fluorogenic, colorimetric, and enzymatic methods.[65–72] Some of these methods are expensive and complex, suffer from limited specificity (and related false alarms), and from a slow response time. Environmental conditions like temperature, pressure, and humidity may also have a significant effect on the performance of these detectors.[65–72] The micromotor sensing strategy adds unique features to the arsenal of CBWA detection schemes based on its distinct 'on-the-move' target isolation and solution-mixing capabilities, capability to access remote locations and fast target–receptor interactions. In particular, this strategy relies on the continuous movement of receptor-modified microengines through complex samples in connection to diverse biomolecular interactions. Such a movement of the receptor through a complex sample leads to a new approach for bioaffinity assays and bioseparations that addresses the limitations associated with the slow analyte transport under quiescent conditions used in such microassays and represents a fundamentally new paradigm in biosensing. The cargo-towing force of modern nanomotors indicates great promise for loading and transporting nanosensors to remote locations. The self-propulsion capability coupled with advanced fabrication technologies used for creating these micromotors has opened up new sensing opportunities and bioanalytical applications and has been shown to be extremely effective in accelerating target–receptor interactions and detection in complex matrices.

4.2. Functionalized micromotors for selective capture, isolation and detection of BWA

Among BWA, *Bacillus anthracis* (*B. anthracis*), which is Gram positive, represents one of the multitude of possibilities exploitable by the military or terrorists and has led to urgent needs for rapid, sensitive, and cost-effective detection and neutralization methods.[67–74] The ability of sporulation and resistance of the spores to harsh environmental conditions (like heat and humidity, disinfectants, and UV radiation) make anthrax the most important BWA.[75,76] The common methodology of decontamination includes bleach, chlorine dioxide, and hydrogen peroxide treatment for the inactivation of *B. anthracis* cells.[77–79] In order to address drawbacks associated with existing technologies, Wang's group[80] reported a micromotor-based approach for the rapid screening, detection, and destruction of anthrax spore simulants from environmental samples. The 'on-the-fly' spore screening protocol relies on the movement of anti-*B. globigii* antibody-functionalized micromotors in a mixed contaminated solution of *B. globigii*, *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli* (*E. coli*). Fig. 4 shows the 'on-the-fly' spore detection protocol which relies on the movement of anti-*B. globigii* antibody-functionalized micromotors in a contaminated solution to recognize, capture and transport single and multiple spores.

The new functionalized micromotors allow for a label-free visual identification of the presence of a threat, while the micromotor-induced mixing accelerates the antibody-binding as well as the spore destruction processes. Unmodified micromotors were successfully used for accelerating the mixing of mild quiescent oxidizing solutions with the concomitant acceleration of cell damage. The self-propulsion capability of micromotors induced efficient fluid mixing at the microscale level and this mixing was shown to be extremely effective in accelerating both spore–receptor interactions and detection. This micromotor-based approach thus offers considerable promise for the development of effective systems that not only alert about the presence of a biological target but also mitigate such threats.

The selective isolation of biological threat targets from untreated complex matrices holds considerable promise for the identification of various pathogens in order to combat terrorism and is one of the most challenging requirements for security monitoring. In particular, receptor-modified tubular microengines offer selective isolation of biological targets from complex untreated samples by capturing and transporting them to a clean environment, thus avoiding laborious sample preparation steps. Such an ability to move the receptor through the contaminated sample is unique compared to traditional detection methods using culture techniques, microscopy, luminescence, enzyme-linked immunosorbent assay (ELISA), and/or the polymerase chain reaction (PCR). Campuzano *et al.*[81] demonstrated a nanomotor-based efficient bacterial isolation platform involving the movement of ConA (lectin extracted from *Canavalia ensiformis*) functionalized microengines to isolate pathogenic bacteria from complex environmental samples. Fig. 5 illustrates the selective bacteria isolation, loading and unloading strategy (catch and release) toward their subsequent reuse, along with the efficient and simultaneous transport of drug nanocarriers. Controlled release of the captured bacteria from a moving microengine was achieved using a low-pH glycine solution able to dissociate the lectin–bacteria complex. Such an ability to isolate and unload target bacteria is essential for identifying pathogenic bacteria serotypes.

Wang *et al.*[82] showed a multifunctional nanomotor with three segments (Au–Ni–Au), which was propelled by ultrasound and guided by the magnetic field using a Ni segment. A concavity was also adopted at the end of the Au segment by the sphere lithography technique to achieve shape asymmetry. Modification of the nanomotor gold surface by using thiol chemistry facilitates functionalization of lectin and antiprotein A antibody bioreceptors which allows capture and transport of *E. coli* and *S. aureus* bacteria, respectively in complex media (Fig. 6). The practical utility of these fuel-free micromotors was illustrated by the isolation and separation of the biological targets *E. coli* and *S. aureus* using ConA and antiprotein A antibody-functionalized micromotors, respectively.

An attractive microchip immunoassay protocol, based on the movement of antibody-functionalized tubular microengines within microchannel networks, was developed by Wang's team.[83] The outermost PEDOT-carboxy layer of the tubular microengine was used to anchor the antibody through EDC/NHS chemistry (Fig. 7). An anti-protein-A modified microengine was used for the selective capture, transport and convenient label-free optical detection of *Staphylococcus aureus* target bacteria (containing protein A in its cell wall) in the presence of a large excess of non-target (*Saccharomyces cerevisiae*) cells. The autonomous transport of antibody-functionalized tubular microengines leads to 'on-the-fly' capture and

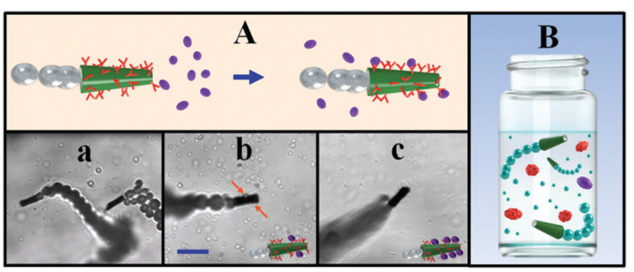

Fig. 4 Functionalized micromotor based isolation, separation and destruction of anthrax spores: (A) schematic illustration of the functionalized micromotors showing capture and isolation of *B. globigii* spores; (a–c) microscopic images illustrating the magnetically-guided functionalized microengines in an aqueous solution transporting target; scale bar 20 μm. (B) Sketch of multiple micromotors for the accelerated destruction of spores. (Reproduced with permission from ref. 80.)

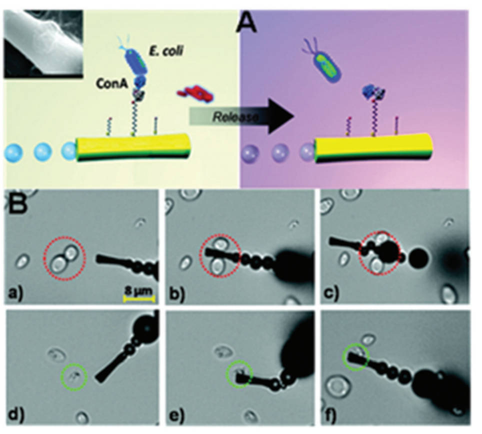

Fig. 5 Lectin-modified microengines for bacteria isolation. (A) the selective pick-up, transport, and release of the target bacteria by ConA-modified microengines, (B) microscopic images, before, during, and after interaction of the modified microengine with a negative control (a–c) and a target (d–f) cells. Scale bar 8 μm. (Reproduced with permission from ref. 81.)

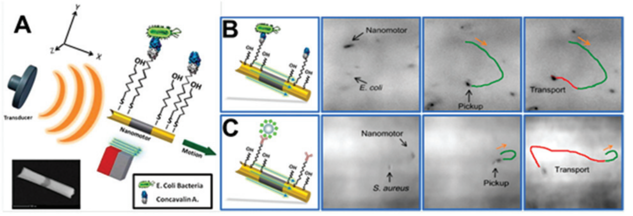

Fig. 6 Ultrasound-propelled magnetically-guided receptor-functionalized nanowire motor for selective capture and transport of biological targets. Capture and transport of (B) *E. coli* bacteria by a lectin-modified nanomotor and of (C) *S. aureus* by Con A-modified ultrasound-propelled nanomotors. (Reproduced with permission from ref. 82.)

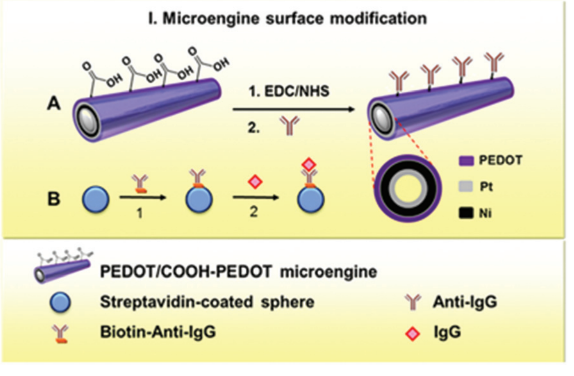

Fig. 7 Design of tubular polymer/metal tubular microengine and its functionalization with antibody using carboxy surface functionalities using EDC/NHS coupling. (Reproduced with permission from ref. 83.)

isolation of the target proteins. All the capture-transport-tag-transport steps involved in the immunoassay protocol were carried out in a microfluidic device, hence replacing the common capture–wash–tag–wash sequence of traditional sandwich immunoassays (*e.g.*, ELISA bioassays well plates). Such a motor-based microchip operation obviates the need for multiple wash steps and results in a simplified immunoassay protocol, and holds considerable promise for diverse defense applications of lab-on-a-chip systems.

4.3. Micromotor-based "on–off" detection of nerve agents

Nerve agents are highly toxic compounds that irreversibly block the enzyme acetylcholinesterase, causing death through the paralysis of respiratory muscles. Recently, Singh *et al.*[84] have reported a dye-coated micromotor based "on-the-fly" fluorescent "on–off" strategy for the rapid detection of sarin and soman related threats within seconds (Fig. 8). The resulting dye-coated micromotors display immediate fluorescence quenching compared to their static counterparts which reflects the crucial role of the micromotor movement in a contaminated solution for the rapid screening of nerve agents. The self-propulsion capability of multiple surface modified micromotors results in a continuous and non-invasive mixing (without agitation), which increases the likelihood of collisions with the target and leads to an increase in the rate of reaction.

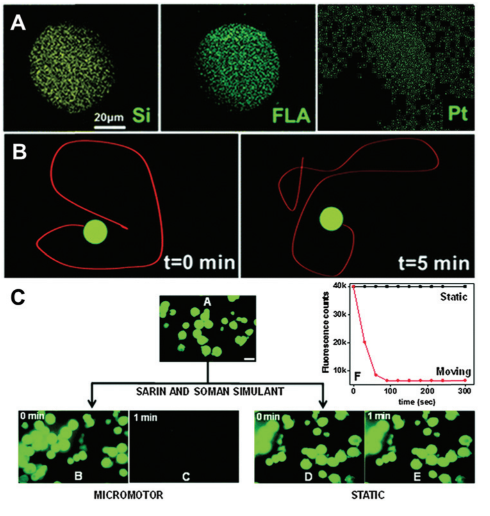

Fig. 8 Micromotor based 'on-the-fly' fluorescent "on–off" detection of nerve agents. The fluorescent intensity of mobile *versus* static FLA coated silica-NH_2 particles before and after exposure to DCP is demonstrated. (A) SEM and EDX images illustrating the distribution of Si, dye, and Pt, (B) tracking line illustrating micromotor movement, and (C) fluorescence intensity of micromotor before and after exposure of a nerve agent. (Reproduced with permission from ref. 84.)

Table 4 Nanomotor-based security detection

Target	Type of motor	Propulsion mechanism	Receptor	Ref.
Anthrax spore *B. globigii*	Tubular micromotor	Bubble propulsion	Anti-*B. globigii* antibody	80
Bacteria *E. coli*	Tubular micromotor	Bubble propulsion	Lectin	81
Bacteria *E. coli*	Nanowire	Ultra sound	Lectin	82
Bacteria *Staphylococcus aureus*	Tubular micromotor	Bubble propulsion	Anti-protein-A	83
CWA simulant Diethyl chlorophosphate	Janus micromotor	Bubble propulsion	NA	84

The fluorescence quenching of micromotors has been attributed to the interruption of the fluorophore's conjugation upon the release of the HCl by-product generated in the DCP-FLA phosphoramidation reaction. These micromotors are very selective to reactive nerve agent simulants compared to non-reactive simulants. Compared to common nerve agent detection methodologies, this "on–off" micromotor-based screening methodology offers real time and field deployable detection in many environmental matrices. Table 4 provides a detailed list of current micromotor efforts towards CBWA detection.

5. Motor-based detoxification of CBWA

5.1. Decontamination

The danger of stockpiled CWA in remote and hostile locations across the globe requires new strategies for decommissioning such sites. Current detoxification protocols require large amounts of reagent solutions, adverse conditions, extended time periods and controlled mechanical agitation. Scientists have thus devoted considerable efforts to develop more efficient approaches for eliminating weapons of mass destruction. Self-propelled micromotors, based on different reactive materials, have shown considerable promise for accelerating detoxification processes, creating a new dimension in handling weapons of mass destruction.[85,86] Decontamination is the conversion of toxic chemicals into harmless products either by destruction or by detoxification. From a methodological point of view, there are four basic methods of decontamination, namely mechanical, physical, chemical and enzymatic decontamination. The former uses mechanical forces to detoxify and works best on large regular surfaces that are readily accessible, while the enzymatic method involves biocatalysts to degrade CWA. Chemical decontamination includes reactive compounds involved in either hydrolysis or elimination or oxidation reactions with enhanced rates to neutralize these completely into non-toxic products. Physical methods include adsorption procedures, washing operation, filtration or dilutions. Recently developed reactive or functionalized micromotors offer attractive CWA physical and chemical decontamination capabilities in environmental matrices, as illustrated and discussed in the following sections. Such a use of self-propelled reactive micromachines accelerates the detoxification processes, enhances the decontamination efficiency and lowers the required levels of the decontaminating agents, thus facilitating the on-site elimination of chemical-agent stockpiles. This micromotor method could be deployed in remote locations where standard detoxification strategies are not feasible.

5.1.1. Motor-based physical decontamination. The effective movement of a micromotor-based remediation platform through polluted water systems can lead to new highly efficient 'move and destroy' remediation protocols.

Removal of CWA using self-propelled activated-carbon micromotors. The coupling of the high adsorption capacity of activated carbon with the rapid movement of these catalytic Janus micromotors has led to a moving adsorptive filter.[87] The resulting self-propelled activated-carbon micromotors offered the highly efficient and greatly accelerated removal of organics such as 2,4-dinitrotoluene, rhodamine 6G, and methyl-paraoxon, as well as heavy metals (*e.g.*, Pb). Such autonomous and directional propulsion was achieved by coating the activated-carbon microparticles with a catalytic Pt hemispheric layer (Fig. 9). The continuous movement of multiple activated carbon/Pt micromotors across contaminated samples, along with the high-density tail of microbubbles (Fig. 9D), resulted in a greatly enhanced fluid dynamics and significantly higher water purification efficiency along with shorter cleanup times compared to non-mobile (static) activated carbon particles. These newly developed Janus micromotors can reach large areas of a contaminated sample, while accelerating the decontamination process without an external mixing force.

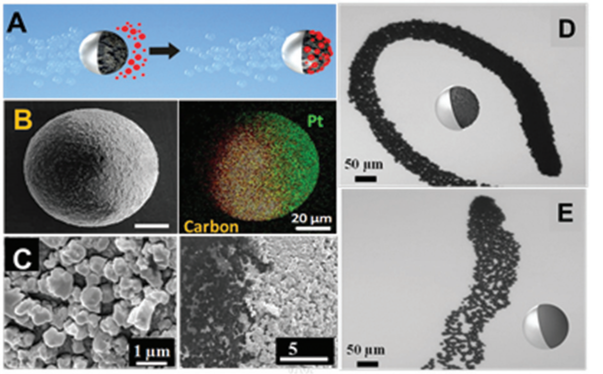

Fig. 9 Activated-carbon/Pt Janus micromotor and its 'on-the-fly' decontamination use. (A) Schematic of the activated carbon/Pt Janus micromotor and its 'on-the-fly' decontamination (B and C) SEM and EDX images for motor characterization, propulsion behavior of (D) activated carbon/Pt, and (E) polystyrene/Pt Janus micromotor. (Reproduced with permission from ref. 87.)

5.1.2. Motor-based chemical decontamination

Micromotor-based detoxification of chemical threats. Effective decontamination of CWA stockpiles requires large quantities of decontaminating reagents, long reaction times, and controlled mechanical agitation, which are extremely challenging under remote field conditions. The destruction of CWA thus requires its transportation to the facilities for remediation. Such transportation poses additional risk for accidents, especially in densely populated areas. Recently developed micromotor-based decontamination protocols (discussed in this review) have the potential to facilitate the detoxification of chemical threats under remote field conditions. Orozco *et al.*[88] demonstrated an attractive approach for the accelerated detoxification of CWA using collective hydrodynamic movement of the micromotors across the remediating solution (Fig. 10).

Taking advantage of the use of hydrogen peroxide as a detoxification reagent and a motor fuel, the accelerated decontamination of CWA was achieved by the greatly enhanced fluid dynamics (self-mixing) and strong OOH^- nucleophile formation associated with the collective movement and

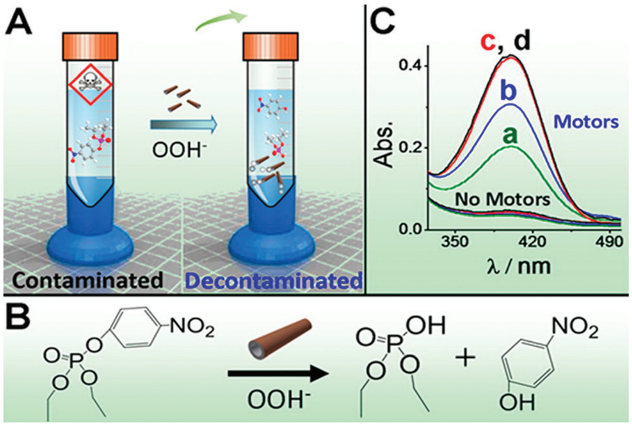

Fig. 10 Micromotor-based accelerated oxidative detoxification of chemical threats under mild conditions through a self-mixing associated with the motor movement and bubble generation. (A) Schematic representation of micromotor based decontamination of paraoxon; (B) reaction scheme showing the involvement of OOH^- nucleophiles and (C) absorption spectra of the p-NP, degradation product of methyl paraoxon with and without micromotor treatment. (Reproduced with permission from ref. 88.)

corresponding bubble generation. The new micromotor decontamination strategy obviates the need for externally powered stirring devices and is expected to enhance the efficiency and speed of decontamination reactions of a broad range of CWA, particularly in field applications.

Photocatalytic destruction is one of the promising techniques for the mineralization of CWA as it does not require harsh reagents, making it one of the most efficient and environmentally friendly processes. Current photocatalytic destruction methodologies for CWA rely on quiescent solutions which make the process less efficient due to the accumulation of intermediate species on the catalyst surface. Catalytic micromotors can enhance these reactions in the presence of reactive oxygen species. Li *et al.*[89] combined the photocatalytic activity of TiO_2 with the environmentally-friendly water-powered propulsion of magnesium-based Janus microspheres. The TiO_2/Mg microspheres act as photocatalytic platforms that propel autonomously in natural contaminated water, obviate the need for a peroxide fuel, and lead to the rapid photocatalytic degradation of CWA. As illustrated in Fig. 11, the presence of the TiO_2 coating, with a small spherical opening of Mg, enables a controlled reaction process and gradual dissolution of the Mg core, leading to a prolonged motor lifetime. UV-irradiated TiO_2/Mg micromotors showed 96% degradation of methyl paraoxon (MP) and bis(4-nitrophenyl phosphate) within 10 min (Fig. 11). In contrast, only a negligible removal of this organophosphorus compound is observed in control experiments, which indicates the crucial role of the TiO_2 photoactive layer and efficient fluid transport which enables effective *in situ* self-cleaning of the TiO_2 surface from adsorbed species, *i.e.*, retention of the photocatalytic activity.

The feasibility of these micromotors was also demonstrated toward the inactivation of *B. globigii* spores, a surrogate

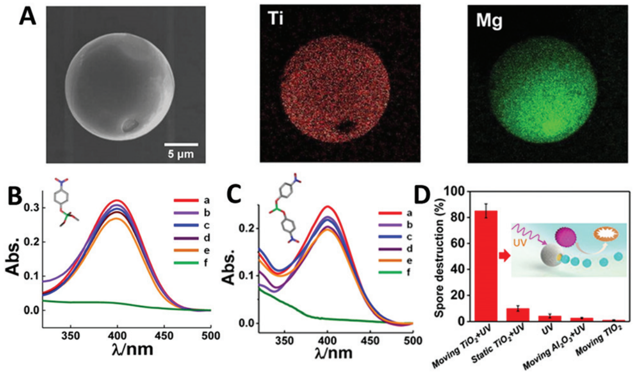

Fig. 11 Micromotor based on-the-fly photocatalytic degradation of CBWA *via* photoactive TiO_2/Mg motors: (A) SEM and EDX images of a titania micromotor with its different components; (B, C) absorbance spectra of p-NP, the degradation product of paraoxon and bis-(4-nitrophenyl phosphate), respectively, with and without micromotor treatment, and (D) statistical plot showing the spore destruction efficiency with the micromotors and different control experiments. (Reproduced with permission from ref. 89.)

species of *B. anthracis* spores. The inherent autonomous movement of TiO_2/Mg micromotors under UV radiation showed significant (86%) damage of the spores compared to less than 10% in control experiments, reflecting the efficient anti-spore activity of the photocatalytic micromotors.

Many adsorbent materials have been used for the removal of CWA. However, due to the lack of reactivity even after several days such adsorbents may lead to secondary contamination of the environment. To overcome this drawback, Singh *et al.*[90] developed multifunctional reactive-cubic-zeolite-based micro-

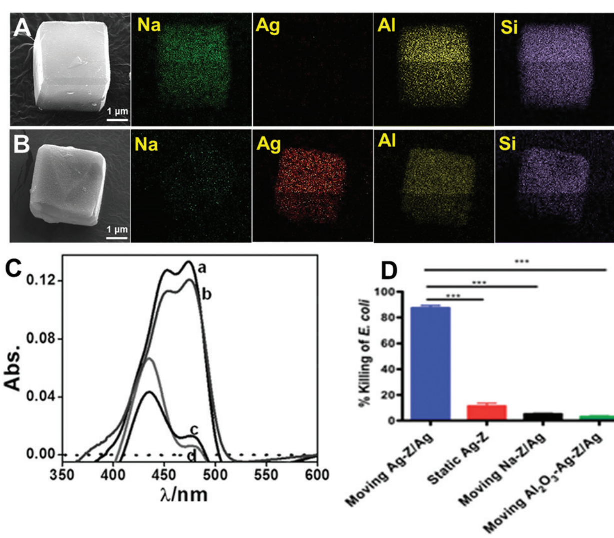

Fig. 12 Zeolite micromotors with effective "on-the-move" CWA degradation and antibacterial activity. (A, B) SEM and EDX images showing the different components of sodium- and silver-exchanged zeolite, respectively, (C) absorbance spectra illustrating the efficiency of micromotor-based decontamination of CWA with control experiments, and (D) statistical plot showing the *E. coli* killing capability of micromotors. (Reproduced with permission from ref. 90.)

motors (Ag–Z) (Fig. 12) by incorporating silver ions (Ag^+) into a aluminosilicate zeolite framework. To impart autonomous and directional propulsion, the zeolite cubic particles were coated with a catalytic Ag layer. The continuous movement of multiple zeolite micromotors and the high-density bubble tail resulted in a greatly enhanced fluid dynamics that led to a high (90%) decontamination efficiency within a short time compared to their static zeolite counterparts. The presence of Ag^+ in the zeolite matrix facilitated the rapid hydrolysis of CWA by the strong binding of CWA with the Ag^+ ion. The same zeolite micromotors were also used successfully for the cytotoxicity against *E. coli* bacteria in order to address potential bacterial infections. Silver-modified zeolite thus displayed a remarkable antimicrobial capability and led to 87.4% killing within 6 min, reflecting the efficient and frequent interaction of zeolite motors with bacteria. Due to the extremely low costs of zeolite and their non-harmful nature, these micromotors can be considered as "disposable micromachines" that obviate the risk of secondary environmental contamination.

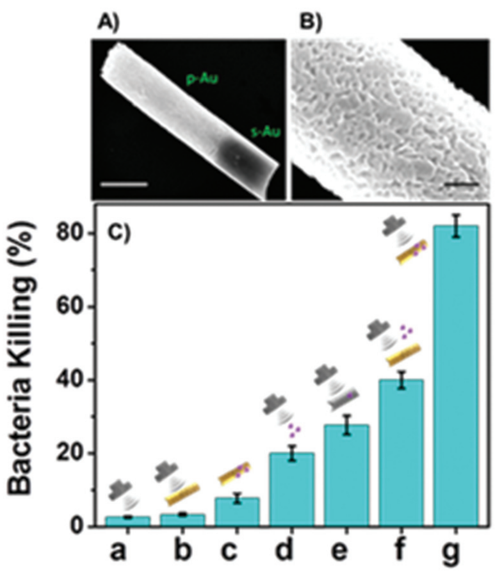

Fig. 13 Fuel-free lysozyme-nanowire based killing of bacteria: (A) SEM images of the Au micromotor and of its (B) nanoporous Au segment; scale bars: 300 and 50 nm, respectively. (C) Bacteria killing efficiency of US-driven lysozyme-immobilized p-AuNW motors using (a) only US without AuNWs, (b) non-functionalized p-AuNWs, (c) static lysozyme-modified p-AuNWs, (d) lysozyme-modified non-porous AuNWs, (e) lysozyme-modified p-AuNWs, (f) free-lysozyme and p-AuNWs, and (g) lysozyme-modified p-AuNWs. (Reproduced with permission from ref. 91.)

5.1.3. Motor-based enzymatic decontamination. In another bio-detoxification study, Kiristi *et al.*[91] fabricated a lysozyme-modified fuel-free nanomotor for the effective and rapid killing of Gram positive *Micrococcus lysodeikticus* bacteria. In this study, the antibacterial properties of lysozymes were coupled with the rapid movement of the nanomotors which promoted enzyme–bacteria interactions and prevented surface aggregation of dead bacteria, resulting in a greatly enhanced bacteria-killing capability.

Fig. 13 illustrates SEM images of the p-AuNWs with a 2 μm length and a diameter of 200 nm and their corresponding bacterial killing efficiency. In this study, large surface area porous gold was introduced into the nanomotor body (Fig. 13B) in order to achieve a higher loading of the enzyme. The motion of multiple lysozyme-loaded US-driven porous nanomotors in bacteria-contaminated samples, and the corresponding fluid mixing, greatly enhanced the bacterial killing capability, leading to an ~30 fold enhancement compared to static micromotors. This study was successfully applied for the killing of Gram positive (84% killing) and Gram negative bacteria. The favorable capabilities of these fuel-free US-driven functionalized antibacterial nanoswimmers along with the biocompatibility of acoustic waves make them extremely attractive for combating infectious diseases while offering defense against bacterial infections. Table 5 summarizes the research efforts directed towards micromotor-based detoxification platforms for CBWA.

6. Conclusions

This review has discussed recent advances in man-made micromotors that have enabled new defense opportunities. Particular emphasis has been given to the ability of artificial micromotors to enhance the detection and elimination of WMD. Considerable progress has been made over the past decade in designing a variety of micro/nanomotors for a variety of security applications. The versatility of the micromotor-based remediation platforms has been shown to enhance the efficiency of detoxification processes of a wide range of chemical and biological threats in diverse matrices. Functionalized micromotors have been shown to be extremely useful for the detection and separation of biological threats, and for responding to the presence of hazardous chemicals by making changes in their swimming behavior. Synthetic micro/nanomotors have thus opened a new horizon for the biodefense

Table 5 Micro/nanomotors-based CBWA detoxification

Type of motor	Target CBWA	Decontamination mechanism	Ref.
Janus (activated carbon/Pt) micromotor	Paraoxon	Adsorption	87
Tubular (PEDOT/Pt) micromotor	Paraoxon	Chemical decontamination; motor induced mixing	88
Titania/Mg microsphere	Paraoxon and *B. Globigii*	Photochemical decontamination	89
Zeolite/Ag Janus microparticles	Diethyl chlorophosphate and *E. coli*	Silver-assisted decontamination	90
Lysozyme modified nanowire	*M. lysodeikticus and E. coli*	Enzymatic cleavage	91

community due to their diverse practical applications. While major progress has been accomplished over the past decade, significant efforts are required to translate these micromotor-based proof-of-concept studies into large-scale field-deployable security applications. Our group is currently developing macroscale motors that cover large areas, towards large-scale security operation.[92] The current reliance of catalytic micro/nanomotors on the common hydrogen peroxide fuel greatly hinders practical security applications of catalytic micromotors. New innovations in materials science at the nanoscale will lead to tiny micromotors based on alternative fuels, different propulsion mechanisms, and advanced reactive materials capable of performing multiple tasks in a smarter and greener way. As future nanomachines become more functional and sophisticated they are expected to perform more demanding security operation. For example, the cargo-towing force of modern nanomotors along with their advanced motion control could eventually be used to collect and bring back sample residues in connection to site verification and monitoring activities. Future efforts could also lead to the use of chemical threat as a fuel for use in chemotaxis to follow its concentration gradients. Further development of such nano/micromotor based systems and protocols is expected to have a profound impact on the ability to respond rapidly and effectively to events which threaten national security.

With proper attention to key challenges, these micro/nanomotors could be used for a wide range of important security applications. New technological breakthroughs will lead to rapid translation of the micromotor research activity into practical defense applications in realistic environments. Given the cutting-edge research in the field of man-made micro/nanoscale machines, we anticipate exciting new ideas and defense applications in the near future, and expect that the micromotor field will have an important role in future efforts to counter major security threats. We thus hope that the present review will stimulate extensive research efforts in the important field of micromotor based chem-biodefense.

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