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Preparedness and response to chemical and biological threats: the role of exposure science

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Abstract

There are multiple components to emergency preparedness and the response to chemical and biological threat agents. The “5Rs” framework (rescue, re-entry, recovery, restoration, and rehabilitation) outlines opportunities to apply exposure science in emergency events. Exposure science provides guidance and refined tools for characterizing, assessing, and reducing risks from catastrophic events, such as the release of hazardous airborne chemicals or biological agents. Important challenges to be met include deployment of assets, including medications, before and after an emergency response situation. Assessment of past studies demonstrates the value of integrating exposure science methods in risk analysis and the management of catastrophic events.

Keywords

hazardous releases; airborne chemical and biological agents; anthrax; emergency preparedness; population exposures; exposure modeling

Introduction

Immediately after the September 11, 2001 attacks on the World Trade Center and the Pentagon, the nation began to expand its homeland security programs in an effort to combat terrorism and to more effectively manage the impact of major natural disasters.¹ An important step was the formation of the Federal Department of Homeland Security in 2002, which combined 22 different federal departments and agencies into a unified, integrated cabinet-level agency.² Since then, many programs have been started, matured, stopped, or changed.³ The Centers for Disease Control and Prevention (CDC) manages the Strategic National Stockpile (SNS; <http://www.cdc.gov/phpr/stockpile/stockpile.htm>), which is the United States’ national repository of antibiotics, vaccines, chemical antidotes, antitoxins,

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Conflicts of interest

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and other critical medical equipment and supplies. However, deployment of medications, medical supplies, and exposure measurement equipment, in anticipation of potential emergency events, is very difficult to arrange because of the amount and types of information required on a number of strategic variables and for decisions that need to be agreed upon by state, federal, and local agencies, in coordination with industry and other stakeholders. Initially, the variables of highest priority can be examined using spatial data-analysis systems, including geographic information systems (GIS), which provide layers of information relevant to terrain, major roadways, public and private buildings, population demographics, and valued infrastructure and assets (targets) in the vicinity of a location, such as a busy train station.^{4–8} Then, intelligence, collected and processed by multiple agencies, regarding historical attempts to cause disruption and chaos, combined with recent findings on documented and suspected illegal activities, can improve the focus of preparedness and response plans. These are important tasks to complete before selecting a particular location for asset deployment, such as the new World Trade Center, and the relevant decision-making process must incorporate elements of exposure science in order to effectively identify and characterize population risks during and after an emergency event.

Exposure science and preparedness

Exposure science can be used to improve components of preparedness and response. Furthermore, the results of exposure analysis can eventually lead to recommendations for the development and implementation of postevent measurement and assessment tools.⁹ The following discussion will focus primarily on the issues associated with exposure characterization and reduction.

The issues involved in using exposure science methods to address terrorist and other emergency event problems have been described by Lioy⁹ and Vallero and Lioy.¹⁰ They are components of the “5Rs” framework, which should be applied in the aftermath of an emergency event of natural or human cause. The 5Rs represent an adaptation and refinement of the response and recovery components comprising two of the four phases (generally identified as (1) mitigation, (2) preparedness, (3) response, and (4) recovery) of standard federal and state frameworks for emergency management (e.g., see the 2012 Congressional Research Service Report R42845 to Congress on Federal Emergency Management). The 5Rs are defined as (1) rescue—setting surviving victims free from confinement or imminent danger by prompt and vigorous action; (2) re-entry—returning to the locations affected by a catastrophe to assess damage and determine the next steps to develop a plan for restoration; (3) recovery—regaining of something lost or taken away, which in a disaster can be the body of a victim; (4) restoration—bringing damaged equipment or other resources to operational status through repairs or replacement or bringing a community or larger area back to full-scale operation after a disaster; and (5) rehabilitation—returning of people to restart operations in a community, building, or facility that had been destroyed or damaged during a catastrophe.

For each of these stages, exposure characterization and assessment are driven by the specific toxic agent and its concentrations, across location and time.^{10,11} The time element is related to the rapidity of implementing exposure measurement activities, the severity of the effects

after an event, and the duration of exposure measurement or estimation activities needed for any or all of the 5Rs. The concept of time associated with the 5Rs is consistent with the definition of exposure, since exposure characterization requires both the specific location and the length of time where and when contact with hazardous agents occurs. The consideration of time profiles of exposure further emphasizes the rate of contact of a person with the toxic agent at a particular location over time because the biological response to an agent depends not only on the total dose but on the transfer rate and the associated biologically effective dose associated with the exposure.^{12–14} A key point is that that short-duration exposures at high concentrations can cause acute effects while longer-term exposures at lower concentrations can cause chronic effects associated with different disease endpoints (e.g., cancer). Bongers *et al.*¹⁵ analyzed a number of different historical chemical incidents and disasters and classified them for collection of exposure data after the event for the purposes of risk assessment and health studies. The types of data collection scenarios are summarized in Table 1 and essentially fit within the rescue and recovery phases of the 5Rs.

These concepts need to be addressed in any medical intervention and victim triage. Accordingly, the information that is needed to minimize the impact of exposure during each of these postevent phases of the 5Rs must be coupled directly to the persistence or duration of exposure that can cause one or more health effects associated with the agents of concern or that can contaminate property and other materials (e.g., food and water). As applied to preparedness, the principles of exposure science within the 5Rs should be addressed and employed in training exercises. More details about the 5Rs are presented in Ref. 10.

Exposure modeling and measurement tools to assist preparedness and response for airborne toxic agents

Before a toxic release and in anticipation of rescue and recovery efforts associated with a resource that could be affected in an emergency event, analyses can be completed to predict the potential impact on the air, water, soil, or food supply and to plan more effective deployment of protective equipment, exposure measurement, and medical-related assets. These analyses will provide information on the sources and pathways that will affect contact and intensity of exposure. What are required are estimates of values for model input variables that correspond to both reasonable and plausible worst-case scenarios. This would include source-emission estimates based on the potential types of catastrophic events; typical and adverse meteorological conditions for the locations of concern; water distribution information; locations of businesses, food outlets, and consumption; the nature of population activities at a given time of the day; and other relevant factors.^{16,17} It is easy to see that this list can become overwhelming and complicated; however, as often discussed, there are many levels of analysis that can be applied to the estimation of the impact of an event involving chemical, physical, or biological agents or a natural disaster on humans and the environment. These estimates can be obtained using a tiered approach involving a suite of modeling and analysis tools ranging from simple/screening to comprehensive (and accordingly resource intensive). They would be employed in a manner consistent with the information available and the urgency of the situation.^{9,15}

To begin explaining these important issues, let us briefly review the analysis of a hypothetical airborne release of anthrax, described in detail by Isukapalli, Liroy, and Georgopoulos.¹⁸ Their analysis first had to address the large uncertainties in the toxicity of the agent and then the variability of exposures and eventual inhaled doses for a potentially exposed population in southwestern New Jersey. A representative sample of virtual individuals in the area of concern was assigned realistic distributions of indoor and outdoor activities following an anthrax-release event. Challenges involved (1) selecting a plausible number of anthrax spores that would cause the disease when inhaled¹⁹ and (2) defining reasonable activities and a representative virtual population for the area predicted to have a high probability of an attack. The analysis employed a standard atmospheric dispersion model (CALPUFF) that is widely used to estimate the concentration patterns of airborne toxicants. However, an important and novel feature of this analysis was the implementation of quantitative exposure characterization involving a detailed stepwise approach for estimating population infectivity for anthrax, summarized in Figure 1. This stepwise approach, implemented through the MENTOR-2E system (Modeling ENvironment for TOrtal Risk studies, version specific to Emergency Events¹²) allowed the estimation of biologically relevant exposures and corresponding adverse effects using microenvironment-specific airborne concentrations and physiologically and activity-relevant variable inhalation rates for each member of the virtual population considered.^{20,21} So, the estimated effective inhaled anthrax doses for members of the representative virtual population accounted for effects such as age, physiological characteristics, and activities. A summary of the modeling results is shown in Table 2, and demonstrates the fact that the estimated number of infections will be significantly affected by human activities and behavior, as well as other parameters that are not typically taken into account in assessing risks from atmospheric releases of hazardous agents. In fact, this modeling analysis indicated that there were reductions of up to two orders of magnitude in the estimated number of infections compared with estimates that were derived using traditional risk-assessment approaches. This difference in estimated impact would have a profound effect on the level of emergency medical service (EMS) response required in an area, the number of units of antibiotic that would be required to treat individuals affected by such an event or suspected of contacting the spores, and the burden on the healthcare system. A related issue had been previously discussed by Georgopoulos *et al.*²² for emergency event victims from a chemical agent release that are expected to be treated by Veteran's Administration hospitals.

A major drawback of the above analysis of risks from a potential release of anthrax spores is that, even if one is able to predict the exposures with sufficient accuracy, the effects from anthrax exposures are not immediate. Thus, the exposed individuals associated with outcomes presented in Table 2 could redistribute themselves over a potentially wide range of distances before the early onset of symptoms associated with the disease. This would preclude easy identification of victims and prevent effective local deployment and distribution of an antibiotic medication. As a result, postevent analyses would require monitoring of emergency rooms (ERs) at regional hospitals or medical centers near and around the affected area to identify victims and start treatment. The anthrax analysis has value in general planning of a response with caveats about the need to examine medical records, hospital ER visits, and admissions to track down and identify victims (individuals)

with anthrax symptoms after an actual event. At the same time, the healthcare personnel working in clinics and hospitals around the location of the event should be provided with updated guidance on anthrax and possibly prophylactic treatment with antibiotics. The latter would be a risk-management decision based on the reasonable likelihood of individuals going to a facility within a reasonable distance from their homes or places of employment. It would also affect deployment of medication and other materials during and after an event involving other types of hazardous releases (e.g., chemical agents).

For highly toxic airborne chemical threats of concern, the types of situations or the timing and complexity of response can be quite variable. For example, depending on the nature and the concentration of the agent, the toxic effects may be immediate, while the toxic exposures at lower concentrations can continue to occur over relatively extended periods of time. A number of toxic agents of concern have been subjected to scientific evaluations that have led to the development of guidelines for acute exposures that range from 10 min up to 8 h in duration. For each of these agents, and for each exposure duration, three acute exposure guideline levels (AEGLs)²³ are defined, addressing exposures that can result in either reversible or irreversible health outcomes or death. Specifically, the three AEGLs²³ are defined as follows. AEGL-1 is the airborne concentration, expressed as parts per million or milligrams per cubic meter (ppm or mg/m³) of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure. AEGL-2 is the airborne concentration (expressed as ppm or mg/m³) of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape. AEGL-3 is the airborne concentration (expressed as ppm or mg/m³) of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.

The above AEGLs are subject to the following evaluation concepts: “Airborne concentrations below AEGL-1 represent exposure levels that can produce mild and progressively increasing but transient and non-disabling odor, taste, and sensory irritation or certain asymptomatic, non-sensory effects. With increasing airborne concentrations above each AEGL, there is a progressive increase in the likelihood of occurrence and the severity of effects described for each corresponding AEGL. Although the AEGL values represent threshold levels for the general public, including susceptible subpopulations, such as infants, children, the elderly, persons with asthma, and those with other illnesses, it is recognized that individuals, subject to unique or idiosyncratic responses, could experience the effects described at concentrations below the corresponding AEGL.”²³ Table 3 summarizes the AEGLs for chlorine that correspond to five different exposure-duration periods, ranging from 10 min to 8 h. For airborne toxic agents, the Nuclear Regulatory Council¹⁷ and Georgopoulos, Liroy, and Computational Chemodynamics Laboratory researchers²⁴ have provided detailed guidance on the multiple levels of analysis of information and modeling associated with characterizing the contaminant dispersion and impact after a release event. Representative types of modeling platforms for a tiered approach that involves increasingly detailed levels of analysis are shown in Figure 2. These platforms provide the algorithms to

estimate airborne concentrations and associated soil and water deposition estimates. The results can be used for screening purposes and/or detailed risk assessments at different degrees of sophistication, which increases from the lower left to the upper right corner of Figure 2. Typical results of an example airborne release— modeling application are shown in Figure 3, which depicts the spatiotemporal patterns and associated impact zones of airborne chlorine as it disperses across an area after a release that could take place as a consequence of a rail-breach accident. The isopleths provide estimated values of airborne chlorine concentrations for points along a gradient from the source to receptors. The dispersing “cloud” of hazardous material is affected not only by meteorology but also by terrain and building types. It is at this point in the data-gathering process where many decisions are usually made about the potential adverse impact on an area, including crude estimates of the number of casualties from a toxic agent event. However, from the standpoint of risk assessment and management, including the deployment of medications to reduce the overall effects of the event on a local population, estimated impacts of these calculated airborne concentrations alone can have a high degree of uncertainty since they do not account for activity patterns, such as time spent in indoor environments by different individuals, and microenvironmental properties, such as ventilation rates of residential, public, and commercial buildings, a point previously made in Refs. 16 and 18.

Since, in contrast to most biological agents, acute health effects from toxic chemicals can begin almost immediately, chemicals with AEGLs can be evaluated more effectively with respect to expected population impacts. However, this point is highly dependent on the ability to respond quickly to the incident with the proper tools for intervention and/or prevention. For these cases, in addition to the implementation of modeling studies to examine the impact of the toxicant release and the assessment of casualties, there are examples of field studies involving tracer gases that can help in understanding the challenges associated with potential releases of airborne hazardous agents in a complex urban environment.²⁵ For example, in the experiment conducted by Liroy *et al.*²⁵ as part of the Urban Dispersion Program (UDP) study in New York City,^{26,27} they collected real-time concentration data from perfluorocarbon tracer (PFT) releases around the Madison Square Garden (MSG) sports complex on March 10, 2005 and observed that local buildings and traffic substantially and routinely affected the dispersal of ground-level tracer releases in the area. The study was eventually repeated in midtown in an area that encompassed Rockefeller Center; in the latter study there were also experiments completed in the New York City subway.²⁸

Other related analyses that have used computational fluid dynamics approaches^{29–31} further reinforce the need to address and characterize various complications associated with tracking released material around urban structures and of documenting associated potential exposures.

From the standpoint of emergency response after a release, some primary issues are (1) who will be able to quickly and safely access the affected area? (2) What is the best strategy for triaging and treating victims? and (3) Who will be qualified and available to successfully administer any assistance in the area after an attack? These are not simple tasks, and they point to the need for strategically identified locations for EMS equipment and personnel and

for storing general types of medicines to relieve symptoms among those who can be triaged and have the potential to survive. It is doubtful that there would be an orderly postevent environment, and EMS and law enforcement will need to be present from the outset to control potential chaos. This issue needs to be thoroughly understood in any realistic preparedness/response exercises. Training exercises should be effectively designed and practiced repeatedly before implementation in an actual event in order to avert a complete response failure. One of the better sets of concepts and protocols that has been designed to protect individuals after an attack has been published for the military.³² Even with these tools, the one situation that cannot be easily planned for is the “surprise terrorist or battle event” that catches all off guard and can only be dealt with in ways that aim to minimize collateral damage and to triage treatable soldiers and other victims.

The series of NRC documents called *Protecting Those Who Serve* were part of an effort to develop a strategic plan that involved six steps for protecting the health of deployed troops.³² Liroy⁹ summarized the components that relate to issues of exposure characterization. For the purposes of the current article, two of the strategies are fundamental to the development of approaches to counteract the impact of an event: strategy 3, the development of risk assessment, risk management and risk communication skills of military leaders at all levels, and strategy 2, the collection and management of environmental data and personnel location, biological samples, and activity data to facilitate analysis of deployment exposures and support clinical care and public health activities. Each of these include activities that reflect the need to make appropriate decisions on the deployment of medical and emergency response personnel and materials, and, ultimately, to reduce exposures. There are three volumes available that outline the strategic plan, but there has not been a formal reassessment of the plan since its publication in 2000.^{32,33} However, there are still lessons to be learned, given the multiple incidents of exposure during more recent war events.^{34–36}

Conclusions

This article summarizes some of the complexities and the challenges associated with achieving preparedness for emergency events involving harmful chemical or biological agents associated with either accidents or deliberate attacks. There is extensive information currently available in reports, manuals, and the scientific literature. There is also the knowledge of many individuals who have had direct experiences with one or more catastrophic events. Unfortunately, each event will have unique components and will present challenges that may have not been seen before. Indeed, multiple questions remain. Can one plan effectively for airborne releases of toxicants? What would be the strategic plan for deployment and implementation within rescue and recovery? Would such a plan be realistic and feasible? How does one implement the phases of the “5Rs” framework involving rescue, re-entry, recovery, restoration, and rehabilitation? On the basis of the assessment of the case studies that were discussed here, it can be stated that available methods, representing the current state of exposure science, can reduce uncertainties and provide valuable insight in assessing the potential impact of chemical and biological threats in emergency events. Therefore, exposure science should be systematically employed for studying, evaluating, and addressing the above questions within a rational risk analysis and management framework.

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Figure 1.

A generalized eight-step flowchart describing the processes involved in assessing risk using a source-to-dose-to-effect framework; this is also referred to as person-oriented population-based exposure modeling (POM/PBEM). This flowchart reflects the structure of the MENTOR approach and provides a general template for comparing the application of risk-assessment systems. A subset of the models appearing in this flowchart was used in the study of Isukapalli, Liroy and Georgopoulos,¹⁸ where details on these steps can be found. NWS, National Weather Service; NCDC, National Climatic Data Center; USGS, U.S. Geological Survey; NLCD, National Land Cover Database; USCB, U.S. Census Bureau; RAMS, Regional Atmospheric Modeling System; ALOHA, Areal Location of Hazardous Atmospheres; HYPACT, Hybrid Particle and Concentration Transport; CHAD, Consolidated Human Activity Database; NHAPS, National Human Activity Pattern Survey; ICRP, International Commission for Radiation Protection; METS, Metabolic Equivalents of Tasks.

Figure 2.

Different levels of atmospheric-dispersion modeling for emergency response situations are applicable depending on the objectives of the analysis and the resources available for it. Simpler/faster models (lower/left of the chart) can be used in real time to help emergency response operations as they take place, while more comprehensive prognostic/diagnostic models (upper/right of the chart) need to be used for detailed analysis and preparation of response plans, as well as for postevent analysis of historical cases. GIS, Geographic Information System; EM, Emergency Management; CAMEO, Computer-Aided Management of Emergency Operations; ALOHA, Areal Location of Hazardous Atmospheres; HPAC, Hazard Prediction Assessment Capability; LLNL-NARAC, Lawrence Livermore National Laboratory National Atmospheric Release Advisory Center; RAMS, Regional Atmospheric Modeling System; HYPACT, Hybrid Particle and Concentration Transport; MENTOR, Modeling Environment for Total Risk studies. Reprinted from Ref. 24.

Figure 3.

Example release scenario—simulation results showing temporal progression of the ground-level impact from a transportation-related chemical release. Location: Trenton, NJ; latitude: 40.23152; longitude: 74.70112; scenario: rail breach; material: chlorine; release type: medium; damage type: moderate; amount: 17,300 lb.; wind direction: northeast; wind speed: 2 m/h; ambient temperature: 32 °F.^{23,24}

Table 1

Scenario types relating exposure data collection for risk assessment and health studies; these scenarios reflect typical situations that have been encountered in characterizations of past emergency events.

Type	Early-phase risk assessment	Late-phase risk assessment
Type #1	No exposure data collected for risk assessment or other purposes	Exposure data collected for health studies
Type #2	Exposure data collected for risk assessment	Exposure data from early phase not used in health studies 1. Not relevant 2. Not collected in study area 3. Crude indicators leading to new data collection
Type #3	Exposure data collected for risk assessment	Exposure data from early phase used in health study, though other data may be collected
Type #4	Exposure data collected for risk assessment and longitudinal health studies	Exposure data from early phase 1. Used in health study 2. Indicate low exposure and no health study required 3. Additional data collected

Note: Adapted from Ref. 15.

Table 2

A comparison of the estimates of probable infections derived through different approaches for exposure and dose–response modeling considering release of a fixed amount of anthrax spores (100 g) in New Jersey (adapted from Ref. 18).

Exposure modeling approach	Dose–response model					
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
I. Scenario A ¹⁹ (simplifying assumptions regarding breathing rates and location)	166,750	119,910	719,160	161,930	172,230	141,310
II. Scenario B ¹⁹ (simplifying assumptions regarding breathing rates and location)	140,660	109,940	525,920	140,910	145,650	124,870
III. Scenario A; EPA EFH ³⁷	85,669	56,020	485,770	75,747	88,549	70,466
IV. Scenario B; EPA EFH ³⁷	71,954	52,118	355,560	70,046	74,994	61,247
V. Scenario A; MENTOR-2E	25,013	15,631	187,840	21,059	25,908	20,472
VI. Scenario B; MENTOR-2E	19,747	12,950	129,420	17,416	20,247	16,458
VII. Screening scenario A/B ¹⁹ (simplifying assumptions regarding breathing rates, location, and plume dispersion)	1,180,932	1,090,121	1,076,816	1,049,390	1,144,563	1,187,637

Note: Total number of probable infections in the study area is shown for the two release scenarios (100 g of anthrax released over (A) 1 h and (B) 10 h). The columns correspond to the different dose–response models used, and the rows correspond to different exposure modeling approaches used.¹⁸ Cases I, III and V assume that the release (scenario A) takes place in 1 h, while cases II, IV and VI assume that the release (scenario B) of the same total amount takes place at a slower rate, over 10 hours; in all cases dispersion and exposures continue after completion of the release. Case VII represents a screening analysis (following the approach of Ref. 19) that is not sensitive to the release rate. Models 1–6 in columns 2–7 refer to different anthrax dose–response models for anthrax infectivity that were identified in the literature (and summarized in Ref. 18). While there is substantial uncertainty with respect to dose–response, it can be seen that employing more precise and realistic methods in the exposure modeling approach reduces the estimated number of potential casualties by over an order of magnitude across different dose–response models.

Table 3Acute exposure guideline levels (AEGLs) for chlorine.³⁸

	Exposure duration				
	10 min	30 min	1 h	4 h	8 h
Chlorine AEGLs (ppm)					
AEGL1	0.50	0.50	0.50	0.50	0.50
AEGL2	2.80	2.80	2.00	1.00	0.71
AEGL3	50.00	28.00	20.00	10.00	7.10